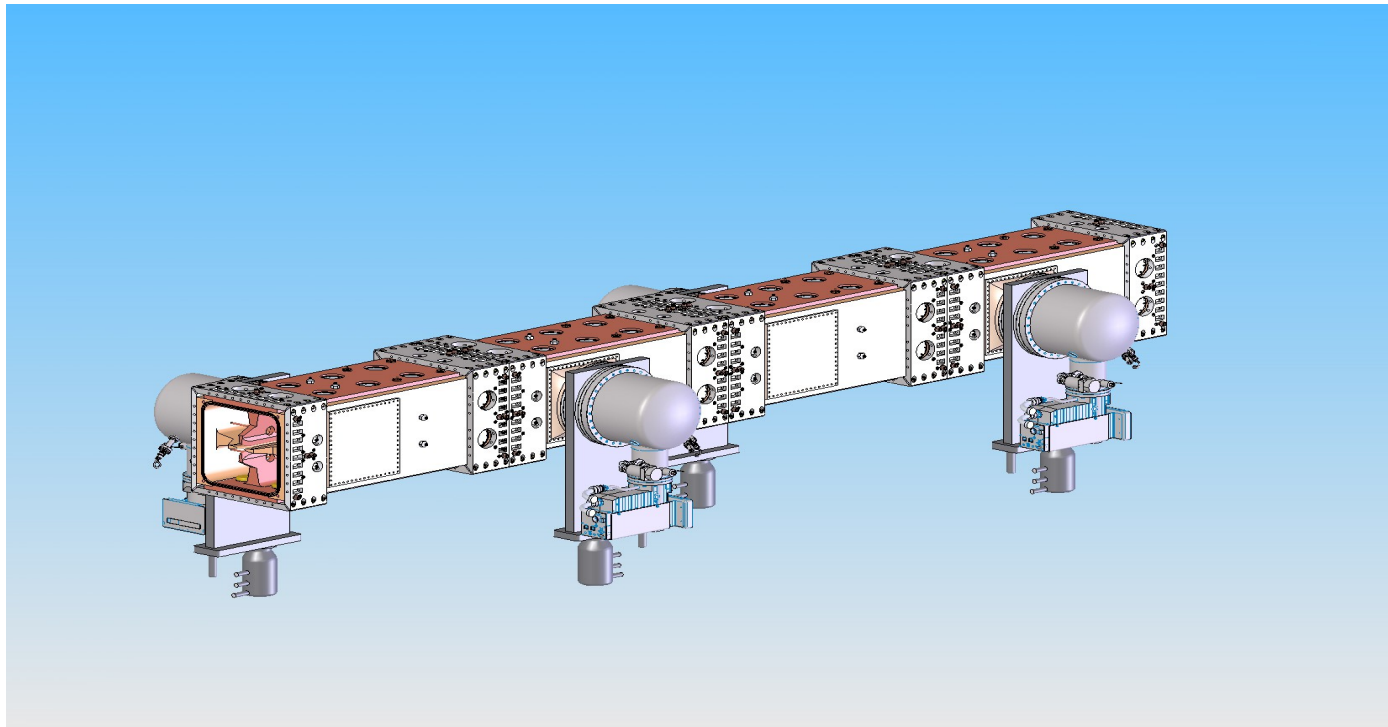


PXIE RFQ Progress

John Staples, LBNL

10-12 April 2012 Collaboration Meeting, LBNL



Summary

LBNL is tasked with the design of RFQs for both FNAL (PXIE) and IMP (Lanzhou)

These two CW RFQs are **very similar**

The beam dynamics and structure design have been converging to nearly a single design, differing only in details of beam parameters.

The mechanical design is compatible with available manufacturing techniques in both China and the USA. E-beam welding is used only on the ends of the gun-drilled water passages.

Both projects are on an accelerated schedule

The beam dynamics design for PXIE and for IMP is complete

From Steve Holmes, September 2011

The scope of the PXIE facility includes:

- CW H⁻ source delivering 5 mA at 30 keV
- LEBT with beam pre-chopping
- CW RFQ operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
- MEBT with integrated wide band chopper and beam absorbers capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing of up to 5 mA average beam current
- Low beta superconducting cryomodules capable of accelerating 1 mA of beam to 15 MeV
- Associated beam diagnostics
- Beam dump capable of accommodating 1 mA at 15 MeV (15 kW) for extended periods.
- Associated utilities and shielding

RFQ Parameter List

	PXIE	IMP	
Input energy	30	35	keV
Output energy	2.1	2.1	MeV
Frequency	162.5	162.5	MHz
DC Current	5-15	5-20	mA
Vane-vane voltage	60	65	kV
Vane Length	444.6	416.2	cm
RF Power	100	110	kW
Beam Power	10.5	21	kW
Duty Factor	100	100	percent
Transverse emittance	<0.15		mm-mrad, rms, normalized
Longitudinal emittance	<1.0		keV-nsec

What's New?

The beam dynamics design is frozen for both machines

At FNAL's request, an exit radial matcher has been added to reduce the divergence of the output beam

Transmission >99% to 10 mA

Transverse emittance <0.15 pi mm-mrad to 10 mA

Longitudinal emittance <0.25 pi mm-mrad (<.78 keV-deg) to 10 mA

Vane length is 443.0 cm, cavity length 444.66 cm

Error analysis of the structure and of the beam dynamics implications carried out

LEBT chopper design integrated with the transverse acceptance of the RFQ

Detailed MWS simulations of the structure (G. Romanov, FNAL) carried out

Design Highlights

Constant cross-section of structure along entire length

constant transverse vane radius: only one form cutter profile needed

The minimum longitudinal vanetip radius = 1.03 cm: easy design of cutter

Four modules, joined with butt joints

Each module assembled with brazes: no electron-beam welding, except to close the ends of the gun-bored water channels.

No complex brazing operations: (No Glidcop in structure)

Wall power density less than 0.7 Watts/cm² CW (SNS was 1.7 at 6% duty factor)

Pi-mode stabilizers offer very large mode separation and field stability against machining errors. 32 stabilizers used: 4 pairs/module.

Mode separation, quadrupole to dipole frequency is 17.5 MHz.

Length only 2.4 free-space wavelengths long (SNS was over 5 wavelengths)

80 tuners, 48 sensing loops, two drive ports

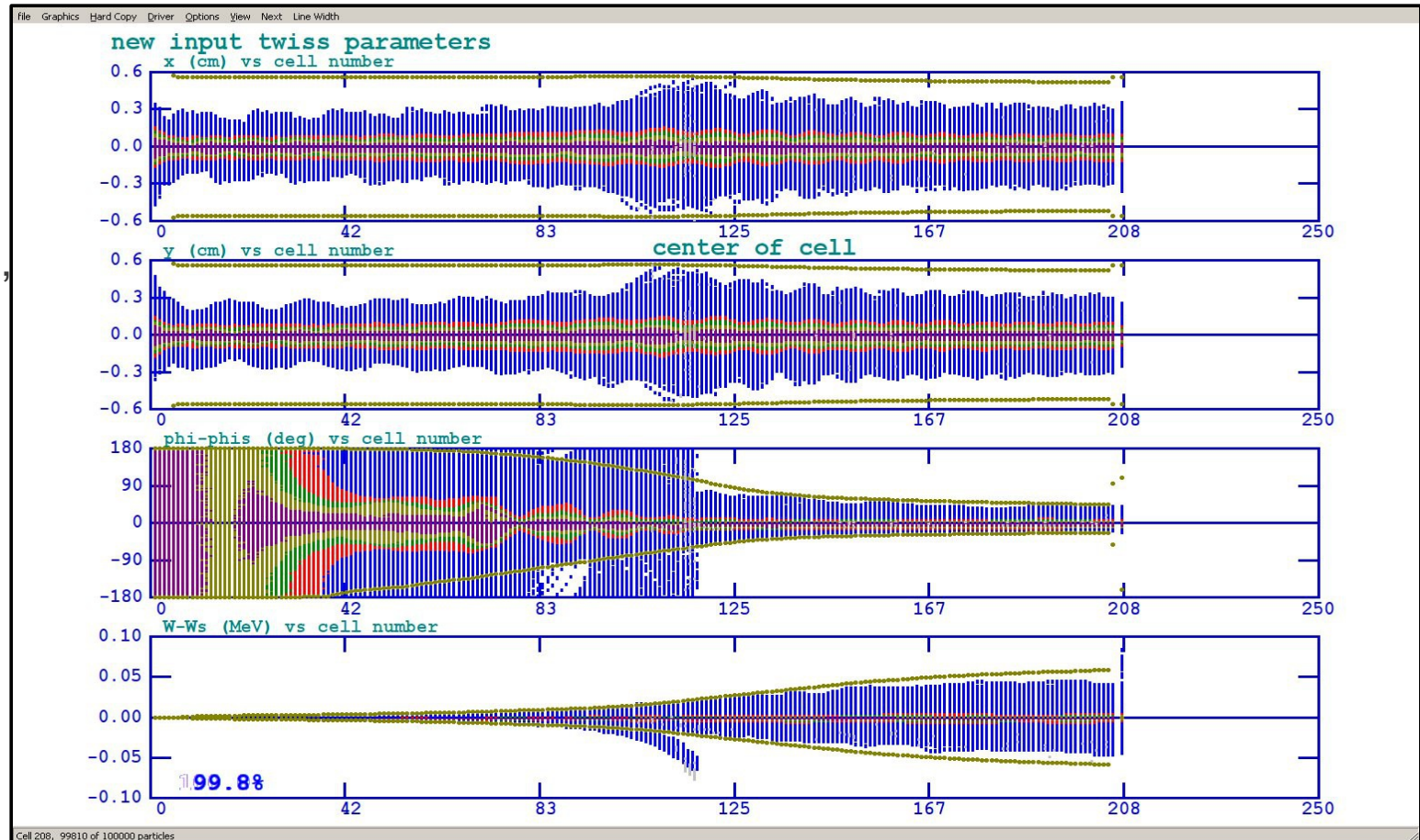
Beam Dynamics Simulations

Beam load derived from ion source
 emittance measurements: halo present
 Capture is 99.81% of 5 mA input beam

Transverse output emittance 0.15 pi mm-mr
 Longitudinal emittance 0.68 keV-nsec

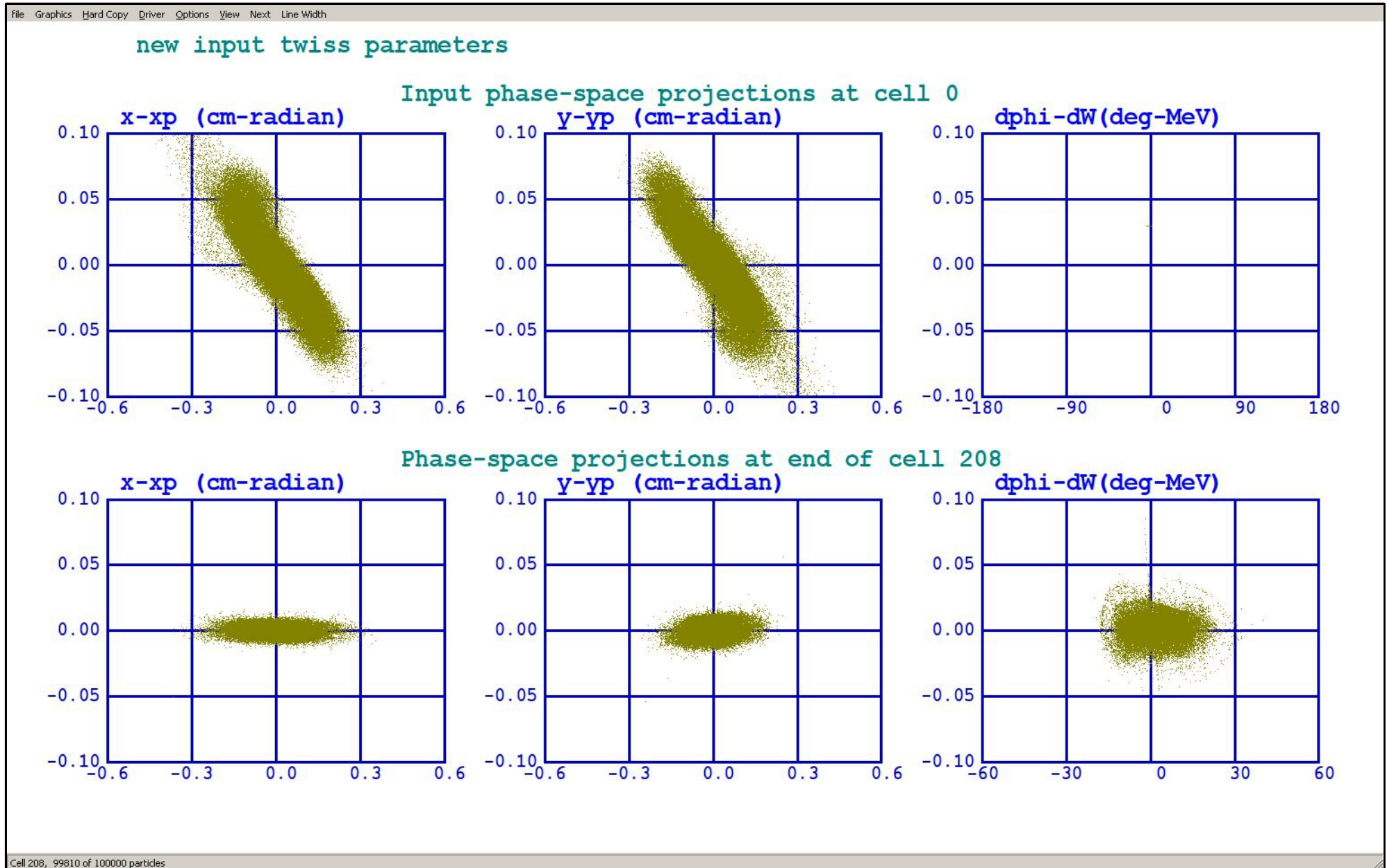
Ellipse parameters at cell 208:				
	alpha	beta	Emit,u,rms	Emit,n,rms
		cm/rad	cm-mrad	cm-mrad
x:	0.1833	23.1221	0.2176	0.01463
y:	-0.0853	11.8872	0.2174	0.01462
		deg/MeV	MeV-deg	MeV-deg
z:	0.0428	1010.4380	0.0396	0.03957
Percent of beam within rms multiples for each phase plane:				
	1rms	2rms	3rms	4rms
x:	42.2	66.5	80.0	87.3
y:	42.2	66.5	80.1	87.2
z:	47.5	70.5	83.3	88.6

Simulation using
 100,000 particles,
 5 mA

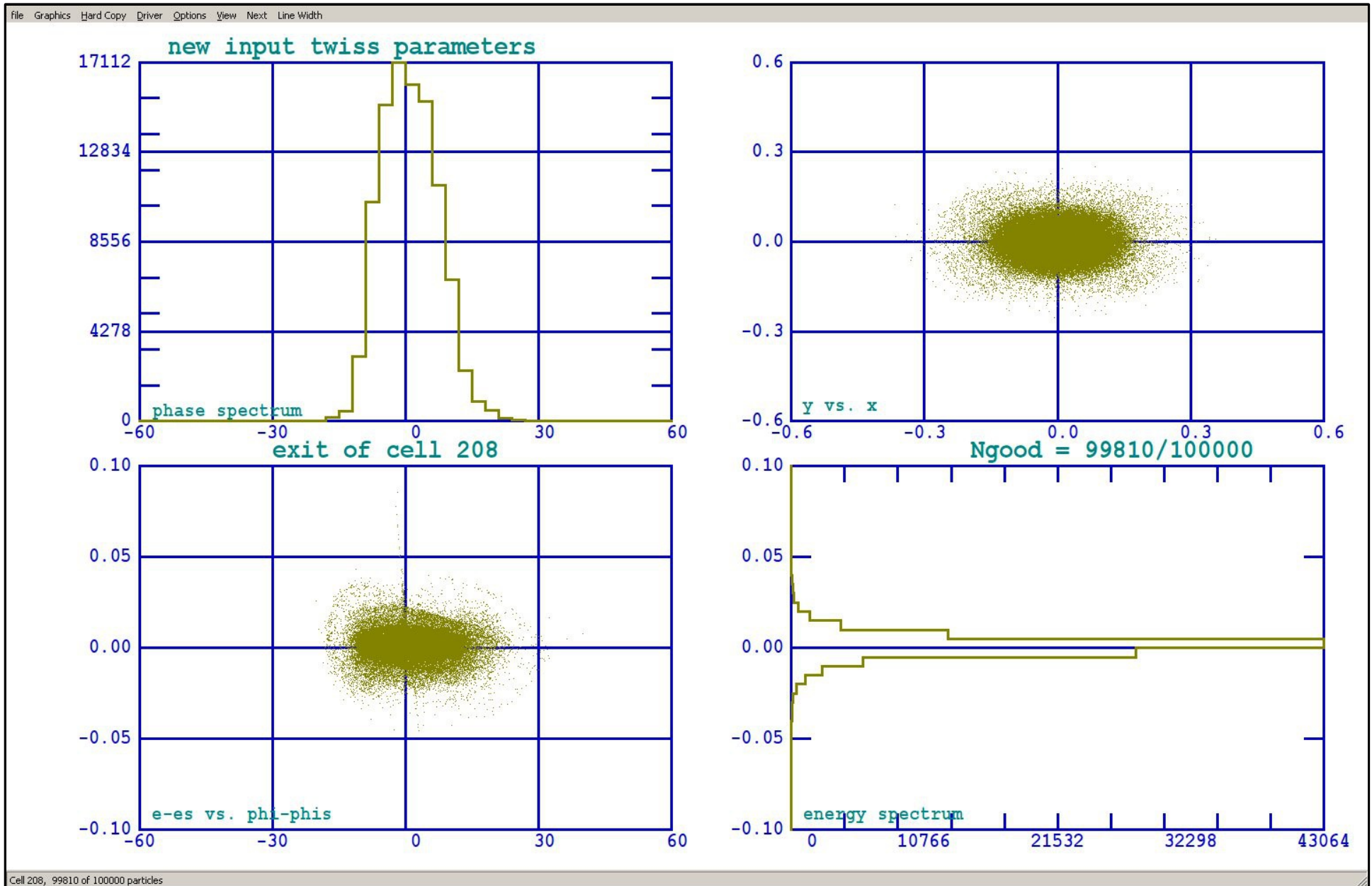


Input and Output phase space plots, 100,000 particles.

Input phase space derived from emittance measurement, include all ion source halo.
Exit radial matcher reduces output beam maximum divergence. Beam at a waist.



Output Phase Space Distributions, x-y and phi-E, 100,000 particles



Vane Dimensions, Exit Radial Matcher

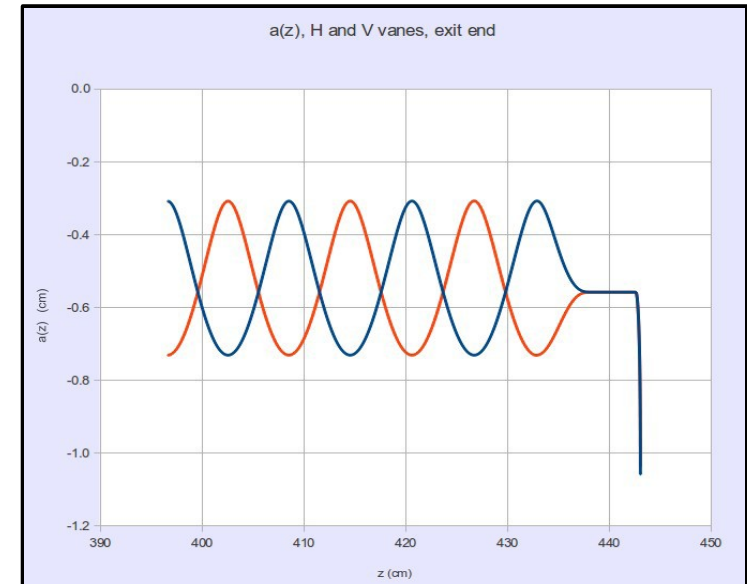
Exit beam nearly at a waist.

Ellipse parameters at cell 208:

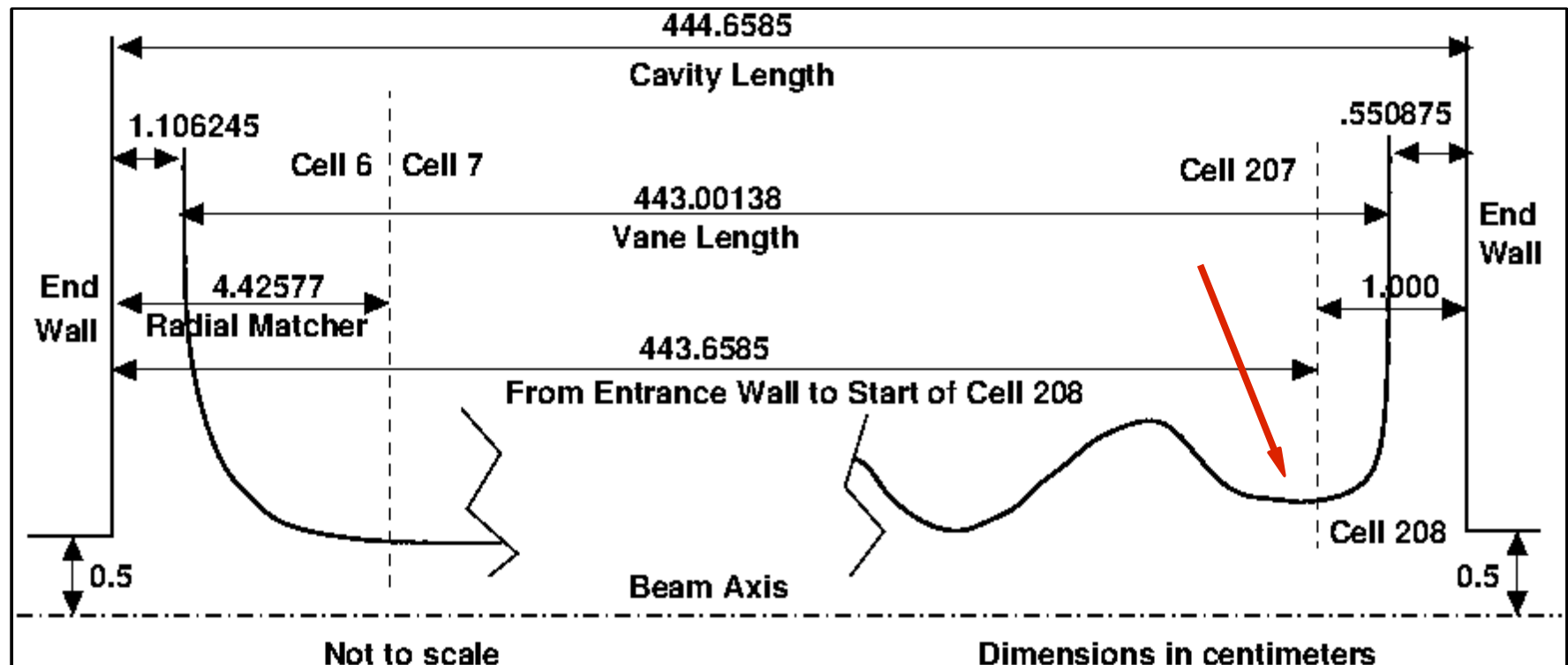
	alpha	beta	Emit,u,rms	Emit,n,rms
		cm/rad	cm-mrad	cm-mrad
x:	0.1833	13.1221	0.2176	0.01463
y:	-0.0853	11.8872	0.2174	0.01462
		deg/MeV	MeV-deg	MeV-deg
z:	0.0428	1010.4380	0.0396	0.03957

Percent of beam within rms multiples for each phase plane:

	1rms	2rms	3rms	4rms	5rms	6rms	7rms	8rms	9rms	10rms
x:	42.2	66.5	80.0	87.3	91.4	94.1	95.9	97.0	97.8	98.4
y:	42.2	66.5	80.1	87.2	91.3	93.9	95.6	96.9	97.8	98.4
z:	47.5	70.5	83.3	88.6	91.2	93.1	94.5	95.7	96.7	97.4



Last few cells of RFQ



Error Analyses

Beam parameters at the end of the RFQ are modeled as a function of:

Input matching conditions as a function of input Twiss parameters

Input current

Input centroid offset created during transition of LEBT chopper

Flat gradient errors

Gradient tilts

Halo content for 100,000 particles

Periodic field oscillation due to the 20 tuners in each quadrant

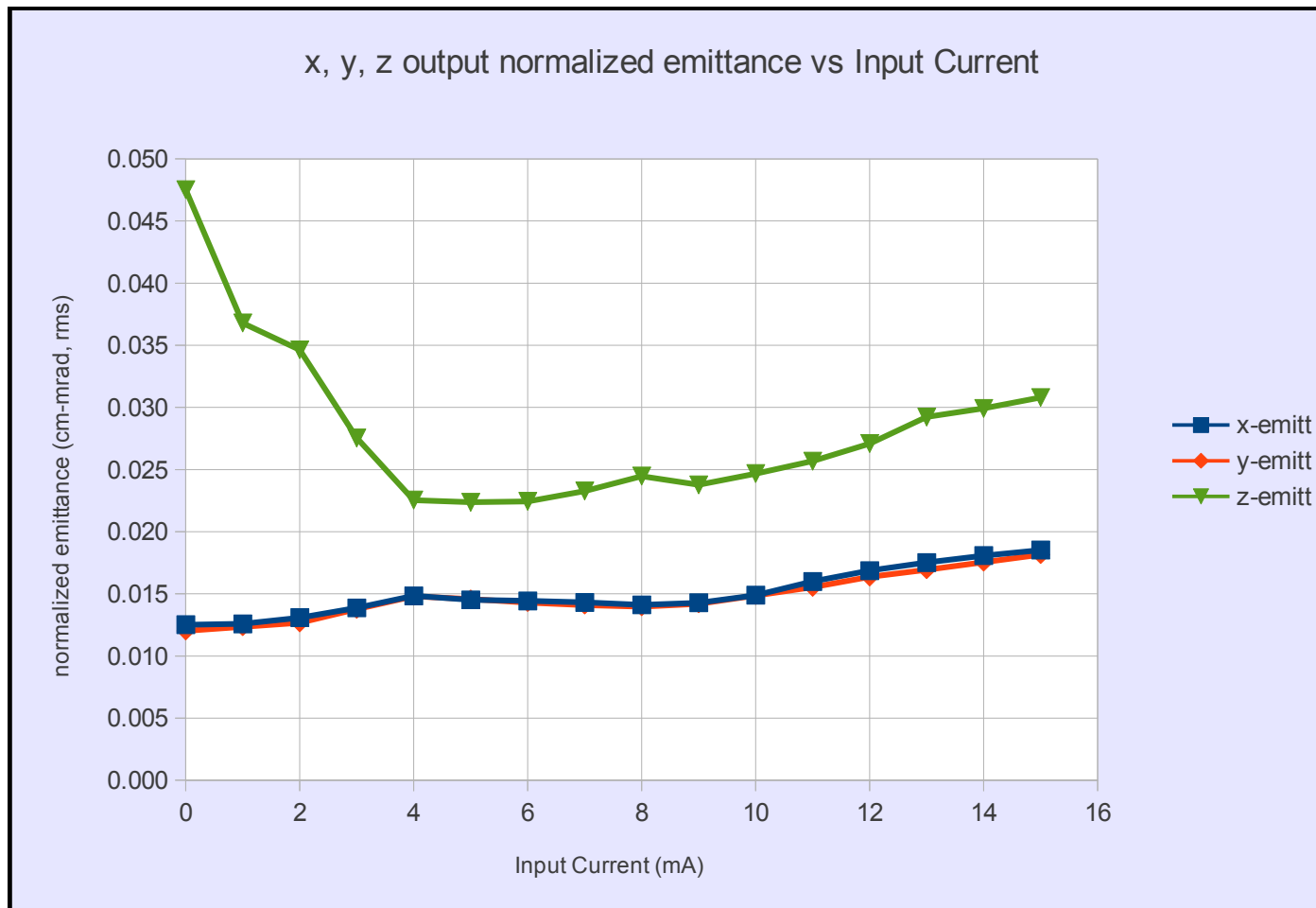
All simulations use a particle distribution based on the measured emittance distribution

All but the 20 tuner errors simulated with PARMTEQM; the tuner error with a modified version of PARMTEQ that allows arbitrary field variations.

Output Emittance vs. Input Current

Optimized input current is 5 mA. Other current values use same input match. Re-matching at other currents may result in lower output emittance, so this represents the worst case away from nominal. The transverse input emittance is 0.011 pi cm-mrad, normalized, rms, derived from emittance scans of the ion source.

Output longitudinal emittance at 5 mA is 0.68 keV-nsec.

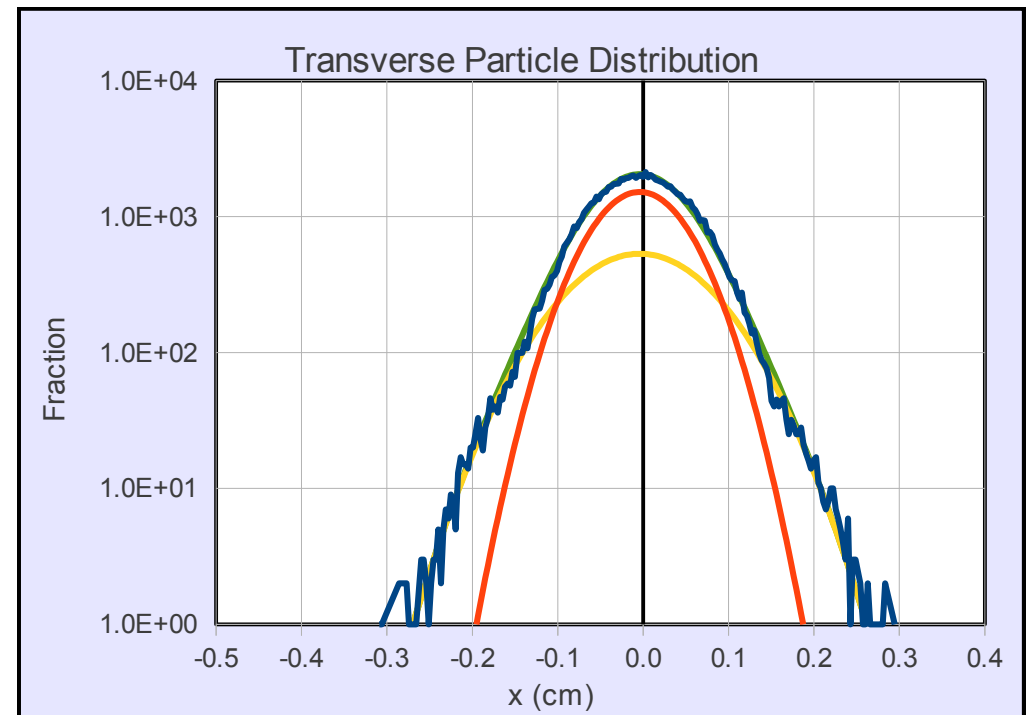


Transverse Particle Distribution

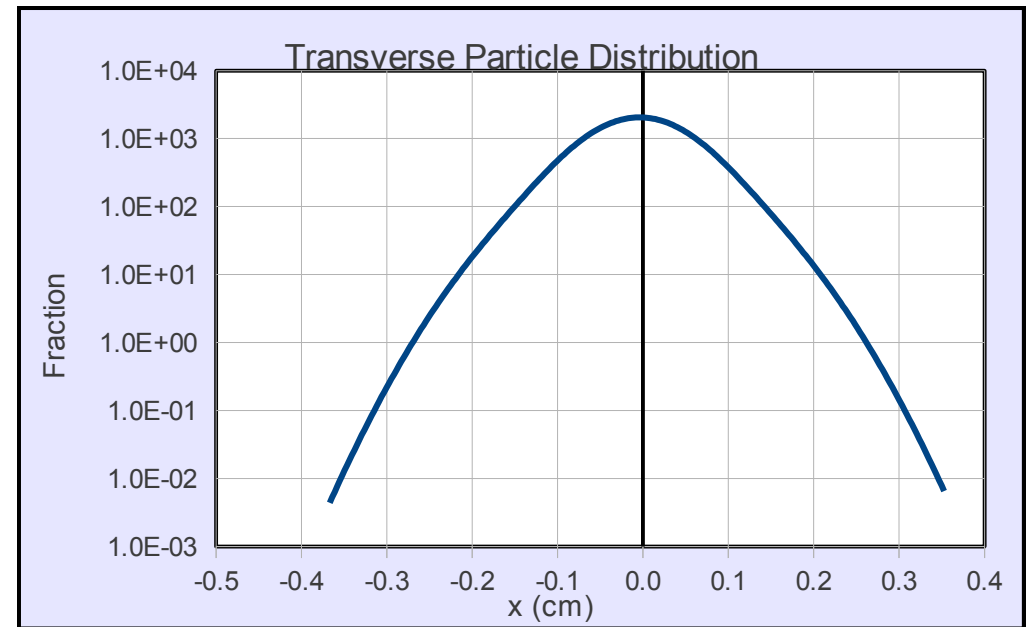
100,000 particles

2-gaussian fit

25% 0.5 mm rms gaussian +
75% 0.74 mm rms gaussian



2 gaussians and original spectrum



fitted spectrum

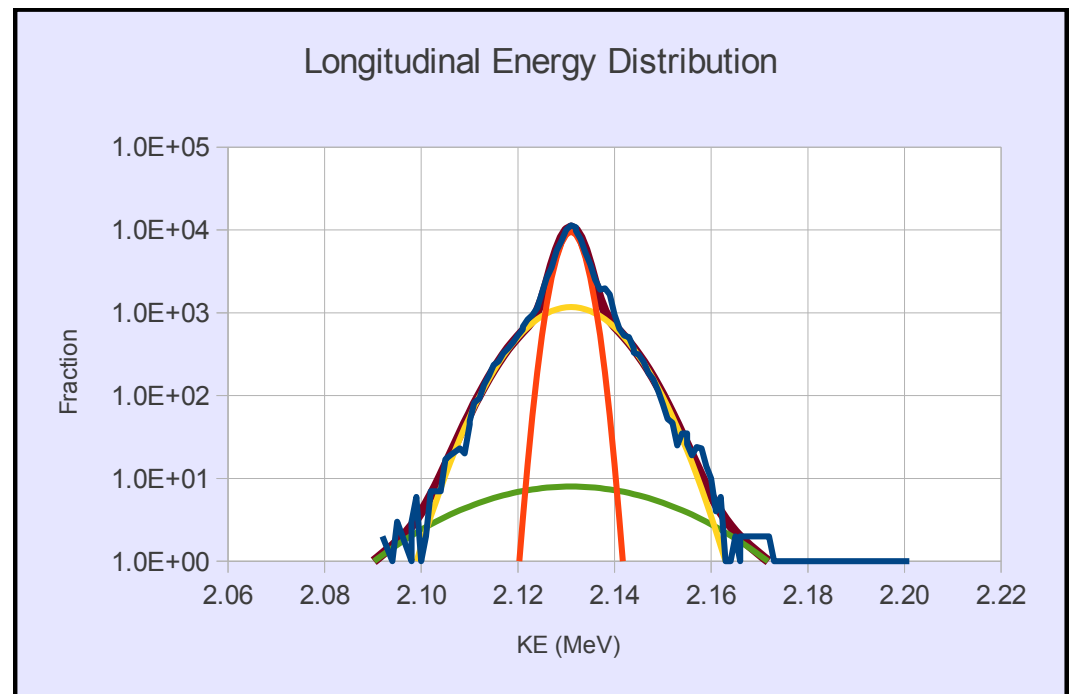
Longitudinal Energy Distribution

100,000 particles

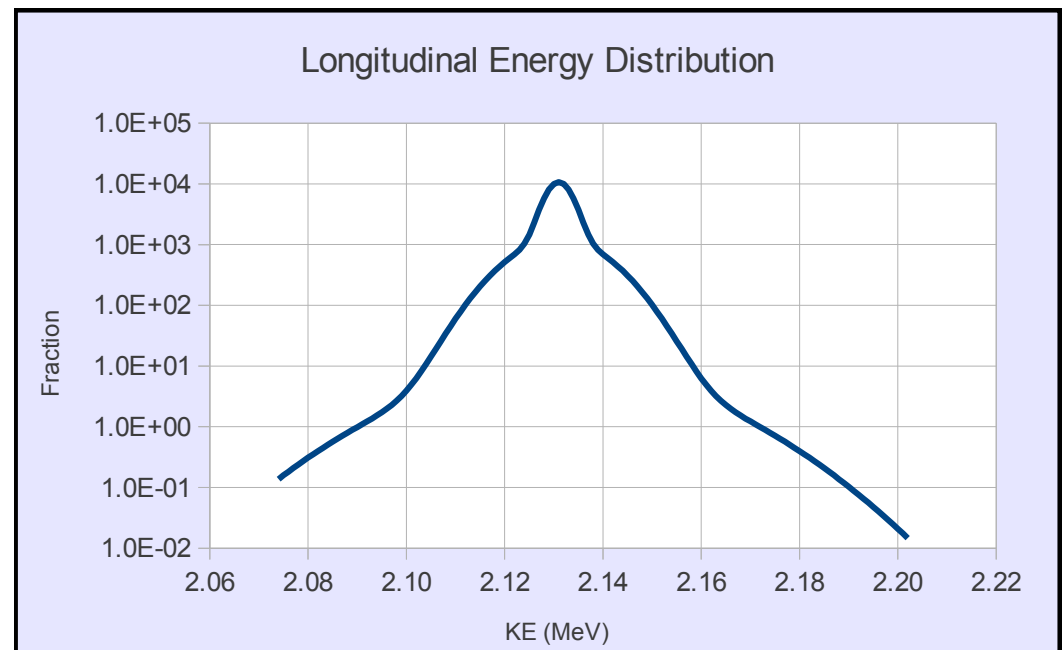
3-gaussian fit

71.5%, 2.5 keV rms spread +
28.0% 8.5 keV rms spread +
0.5% 20 keV rms spread

The 20 keV component has a
very large error bar, as it includes
only a few particles.



3 gaussians and the original spectrum

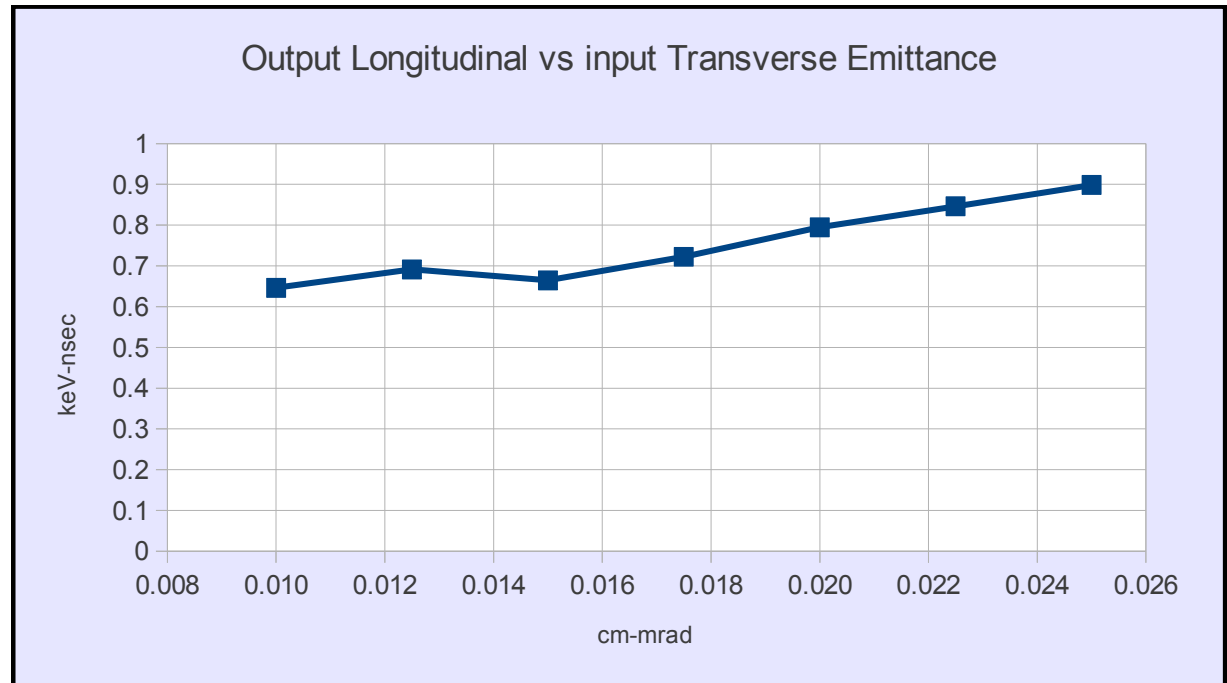


The fitted spectrum

Independent Parameter:

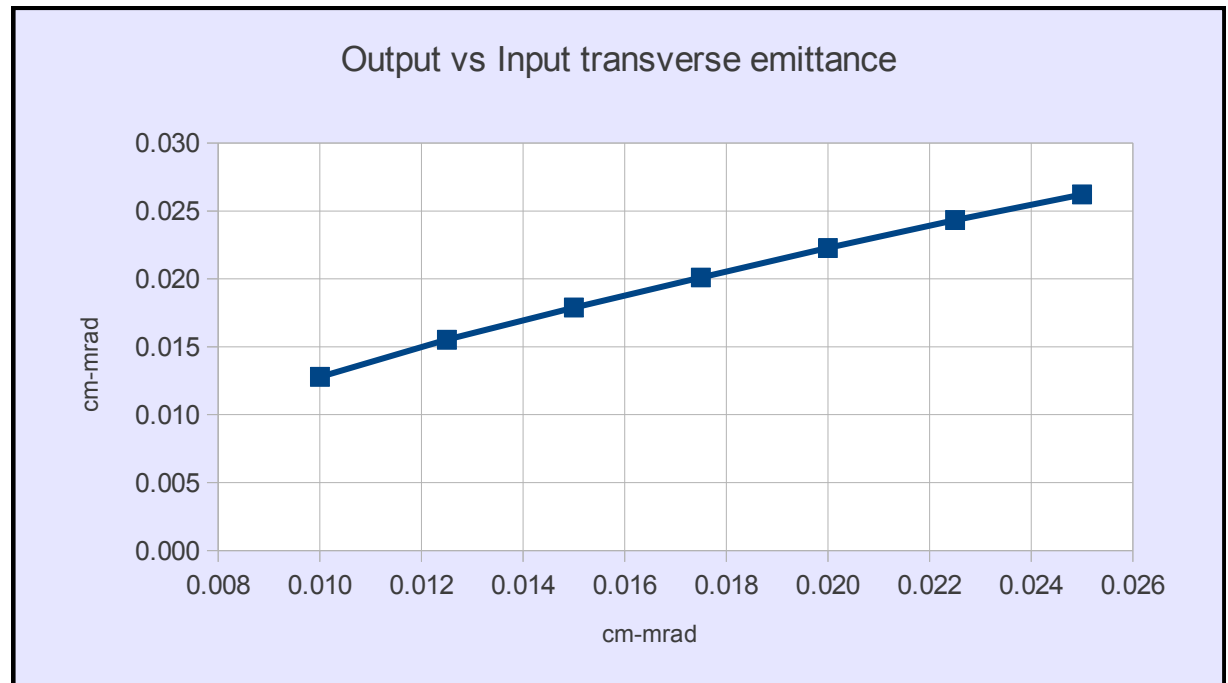
Transverse input emittance.

Output longitudinal emittance as a function of transverse input emittance.



Output transverse emittance as a function of transverse input emittance.

17% transverse emittance growth for input emittance of 0.15 mm-mrad.



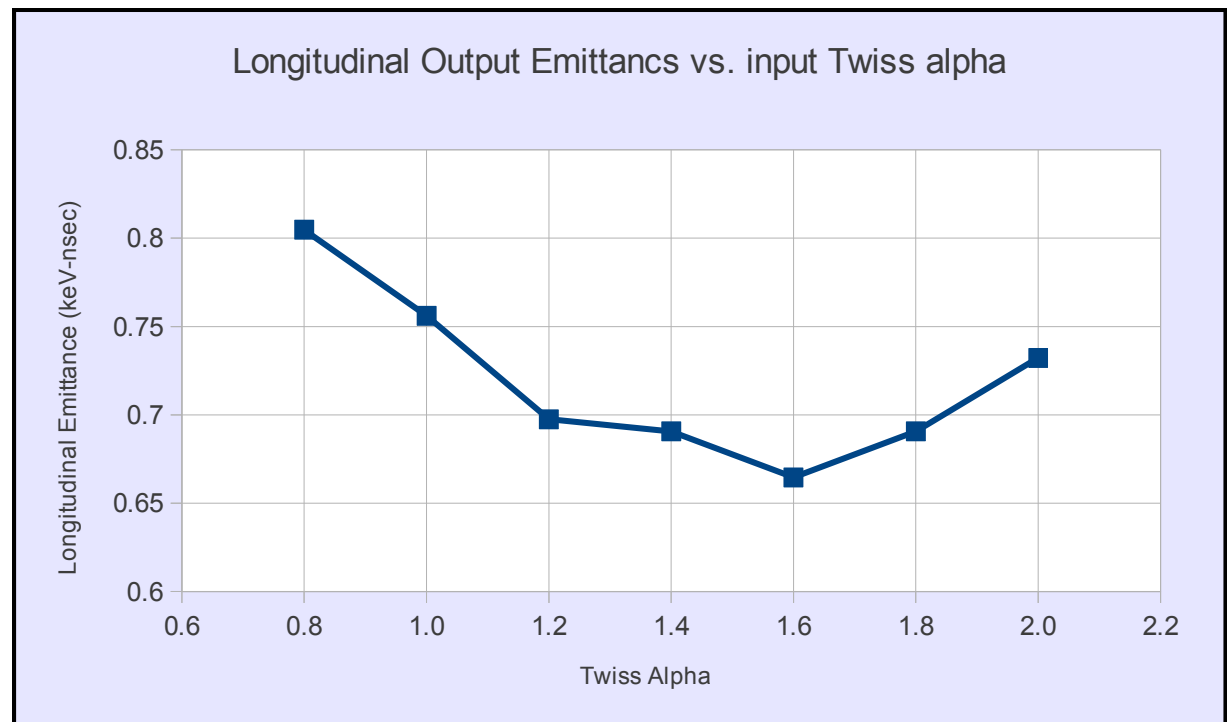
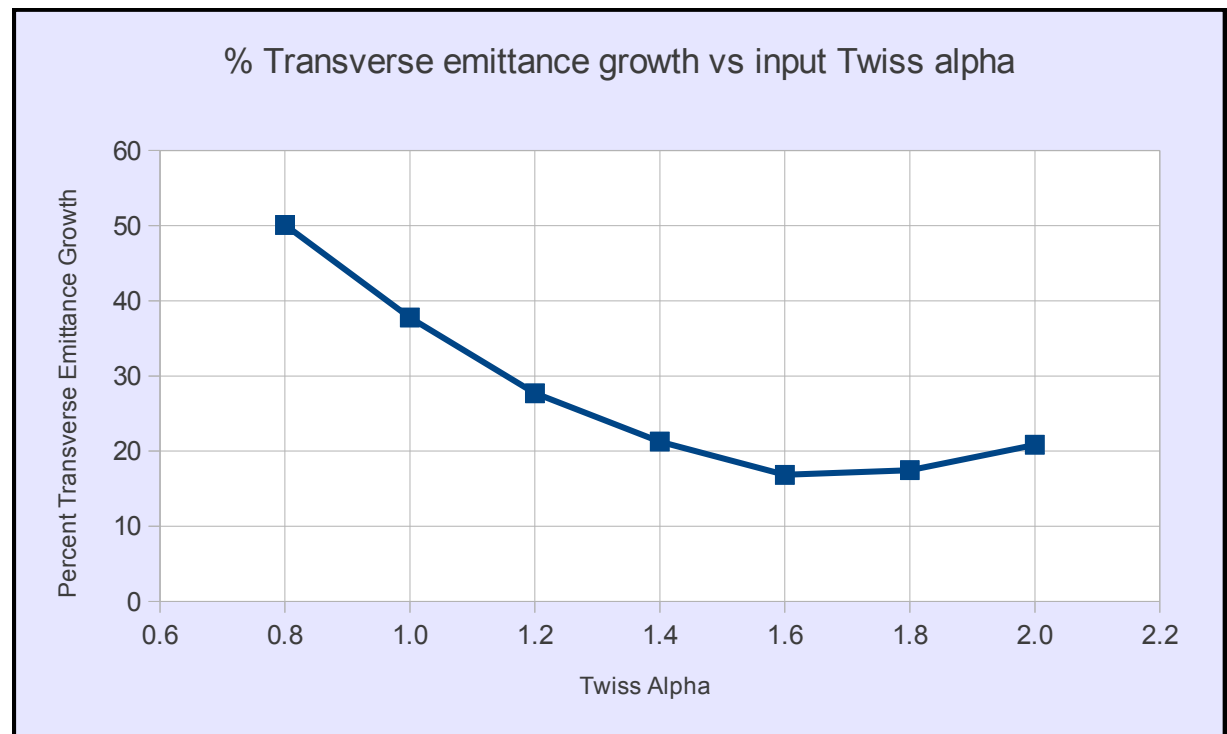
Independent Parameter:

Input Twiss alpha

Output transverse and longitudinal emittance as a function of mismatch of Twiss parameter alpha at RFQ entrance.

Nominal value of alpha is 1.6.

5 mA input current.



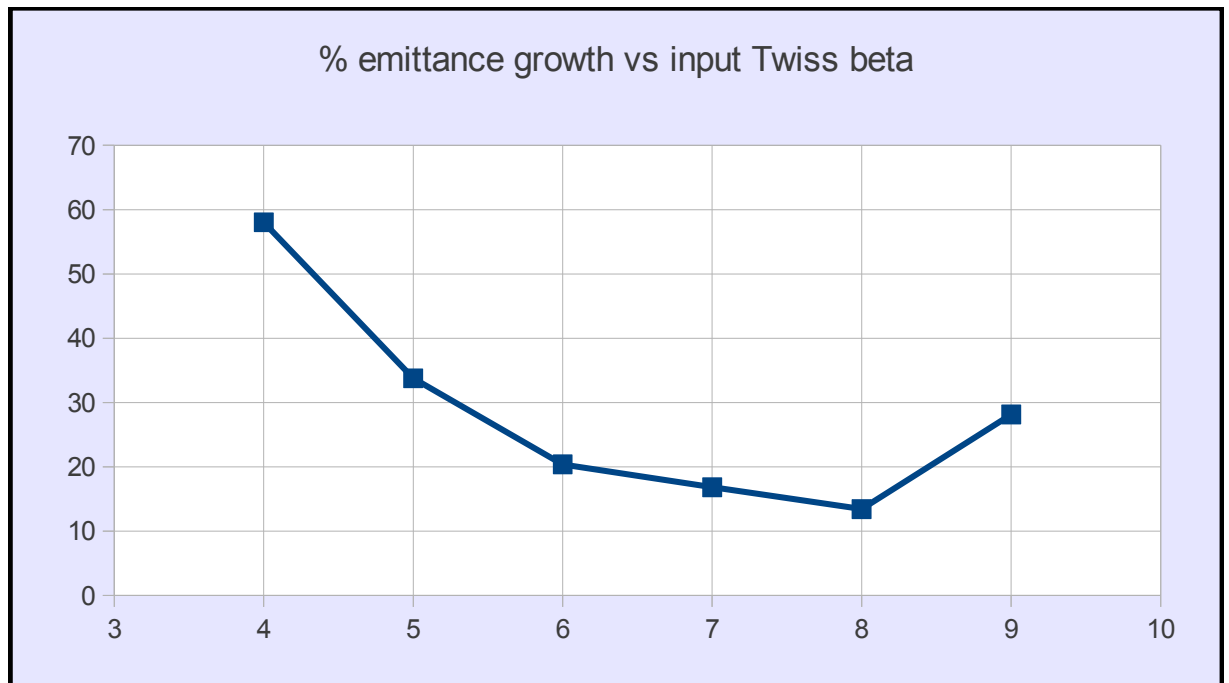
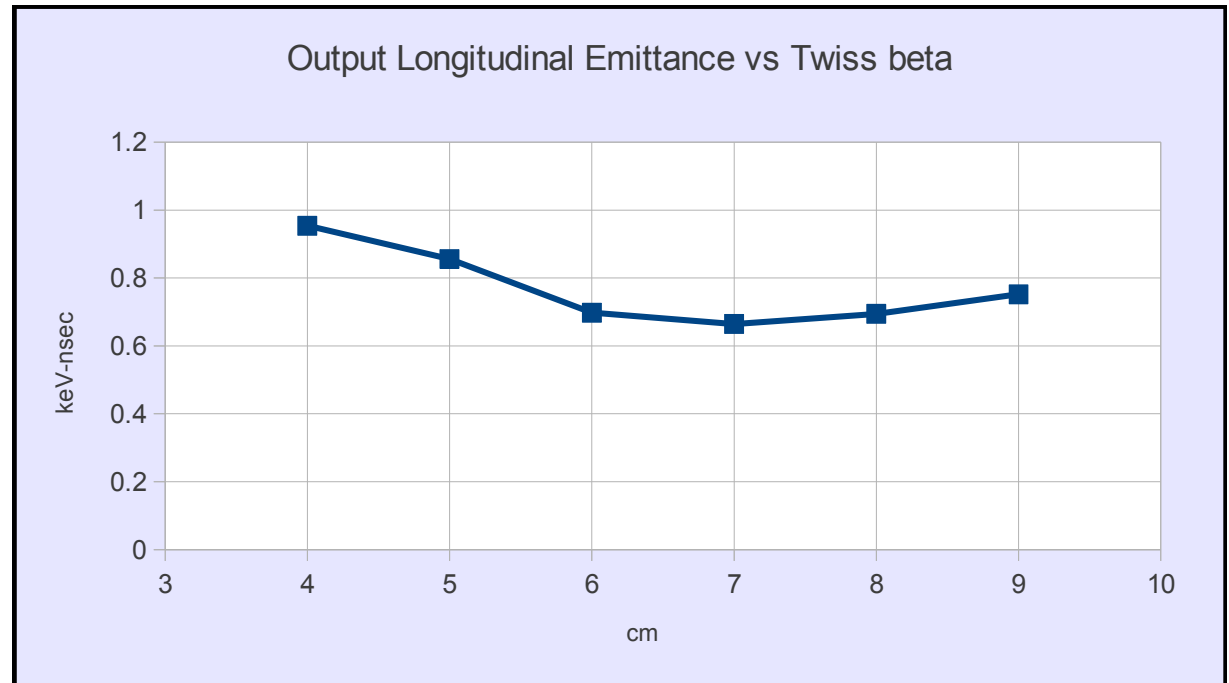
Independent Parameter:

Input Twiss beta

Output transverse and longitudinal emittance as a function of mismatch of Twiss parameter beta at RFQ entrance.

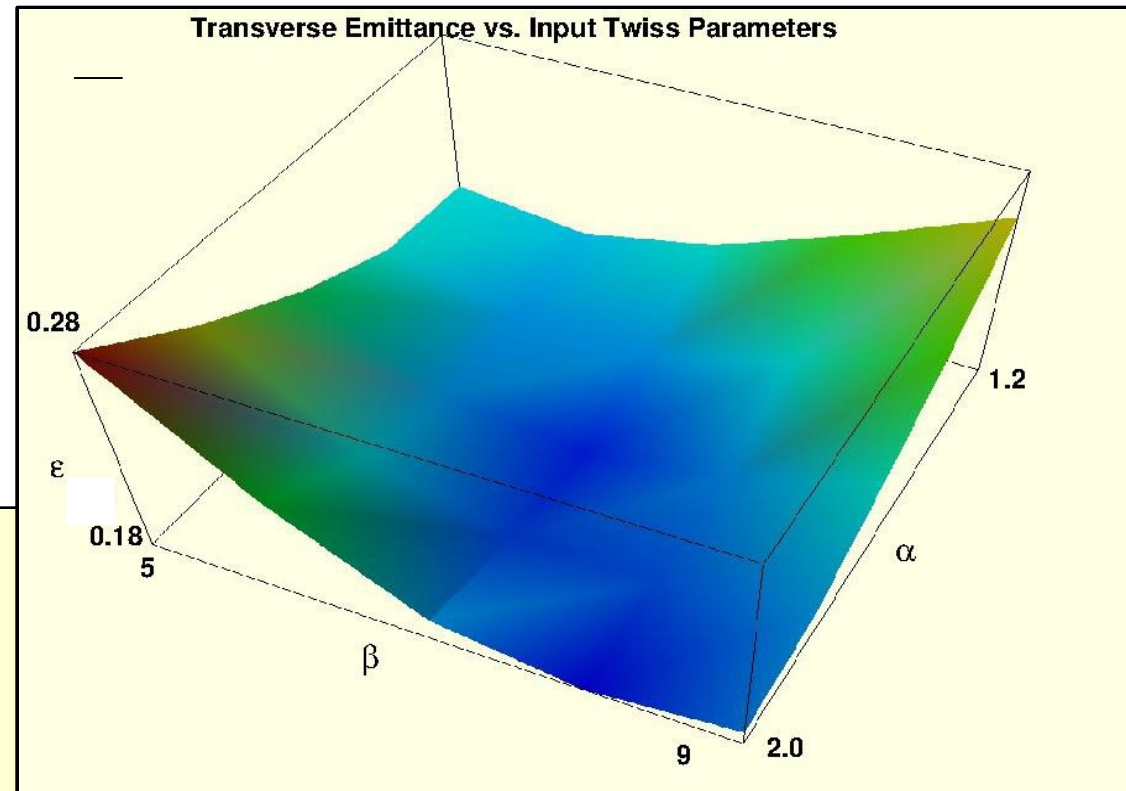
Nominal value of beta is 7 cm.

5 mA input current.

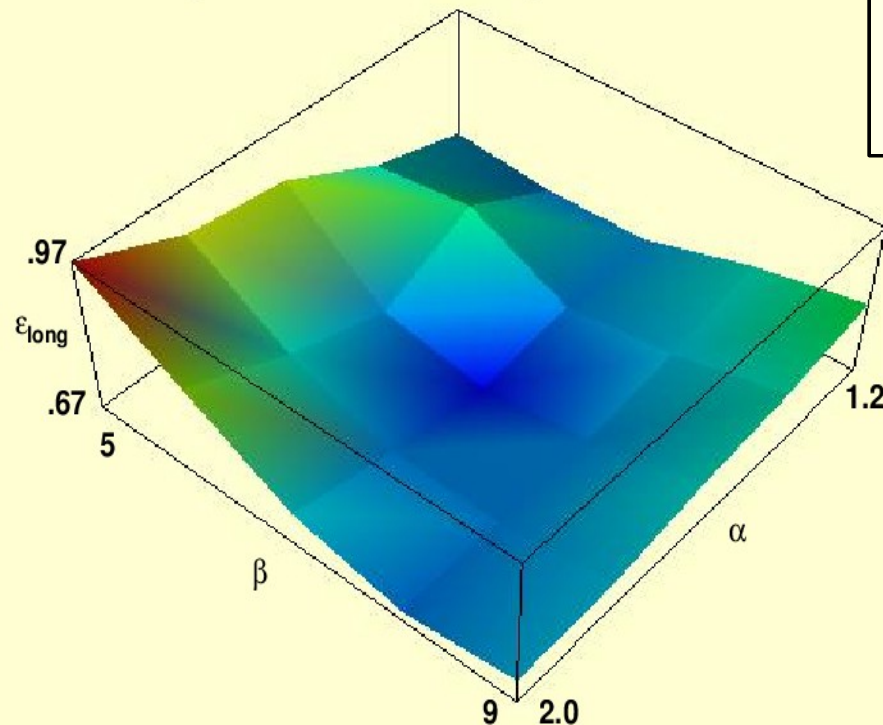


Scan of Output Emittance vs. Input Twiss Parameters

The output emittances are **minimized for the nominal value** of the input Twiss parameters. Transmission is greater than **99%** for all cases.



Longitudinal Emittance vs. Input Twiss Parameters



5 x 5 scan of input Twiss parameters

Nominal input match:

Alpha = 1.6

Beta = 0.07 m (7 cm)

Scan beta from 0.05 to 0.09 meters

Scan alpha from 1.2 to 2.0

Output Beam Parameters vs. RFQ Field Errors

Errors Considered

Flat-field gradient error

Field tilt error, field held constant at entrance

Field tilt error, field held constant at exit

Field ripple error from the tuners

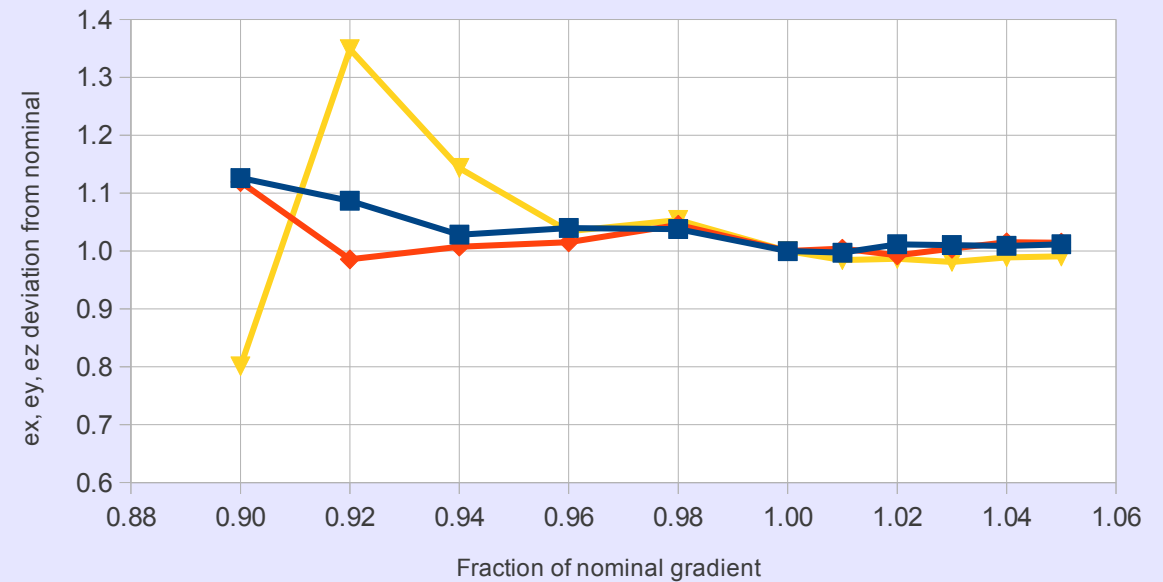
PARMTEQM can only simulate the first three: the field ripple is simulated with another version of parmteq with arbitrary field error.

Independent Parameter:

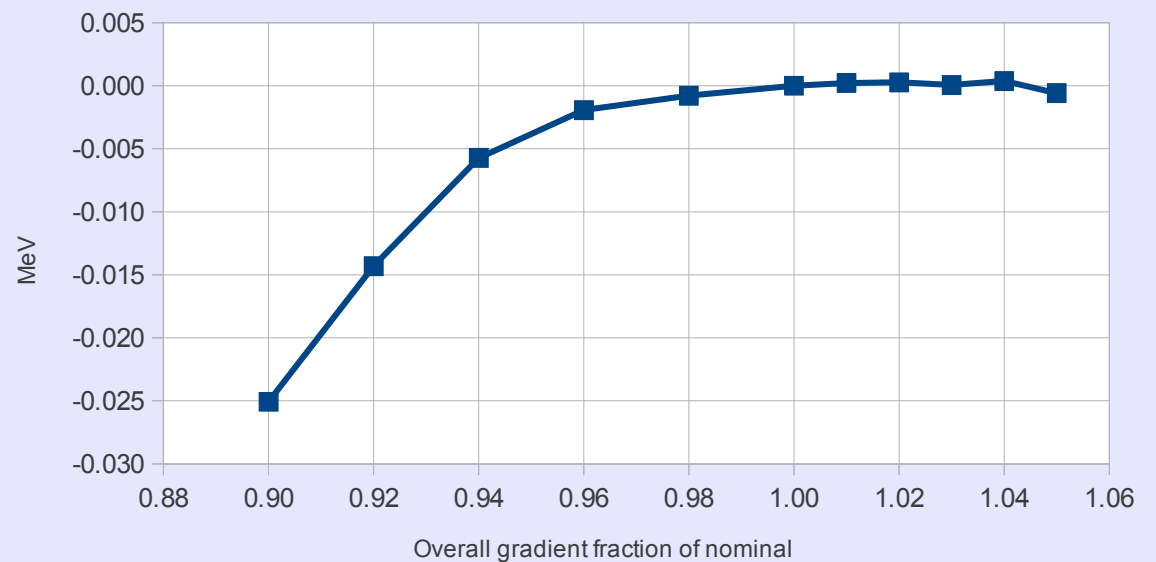
Flat field gradient

Output emittance and deviation from nominal 2.13 MeV output energy as a function of flat gradient error.

Fractional emittance variation vs. field gradient



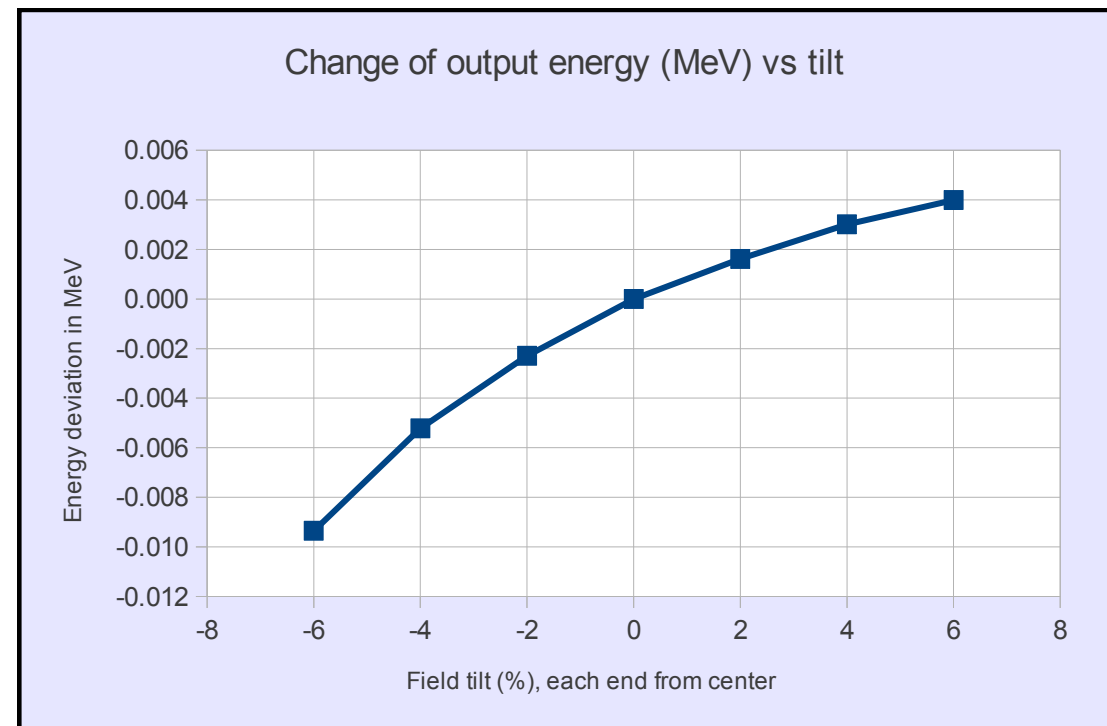
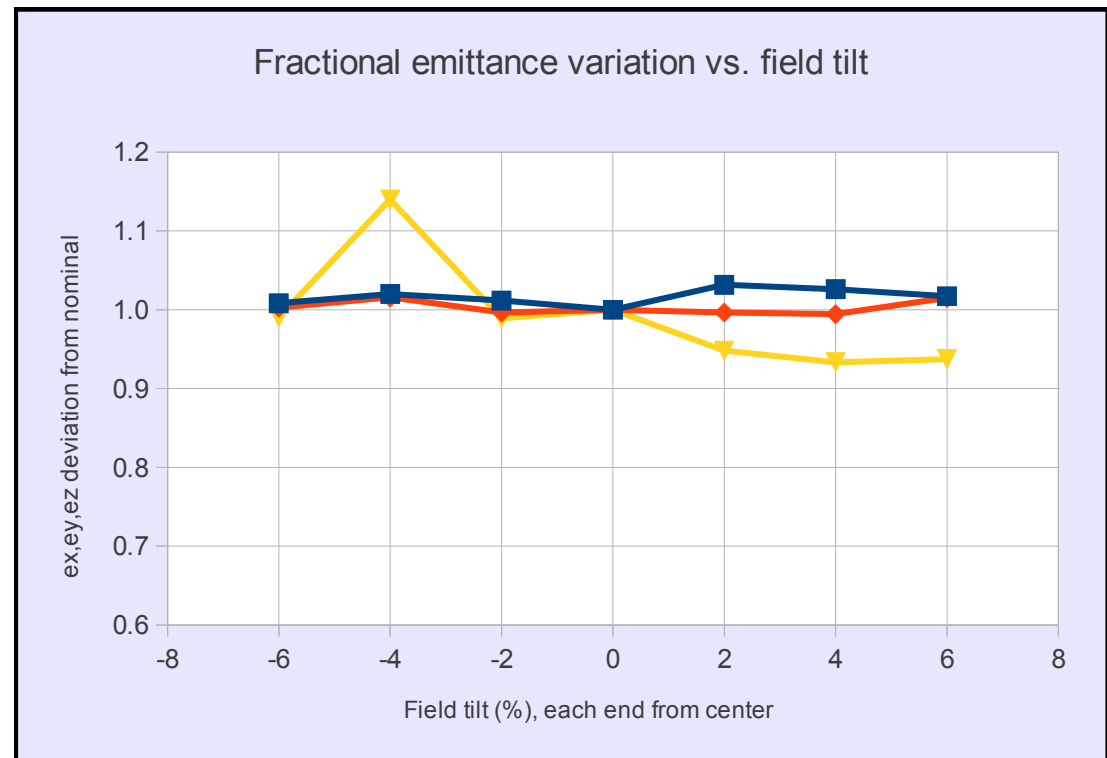
Output Energy Deviation (MeV) vs gradient



Independent Parameter:

Overall field tilt

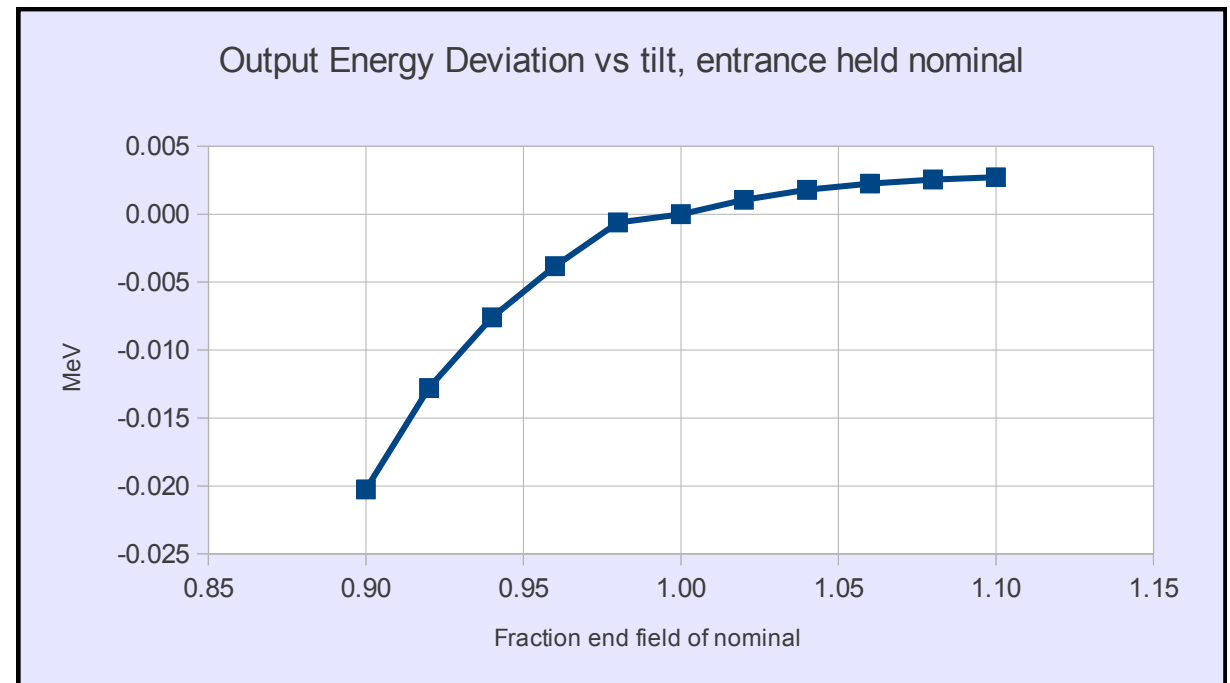
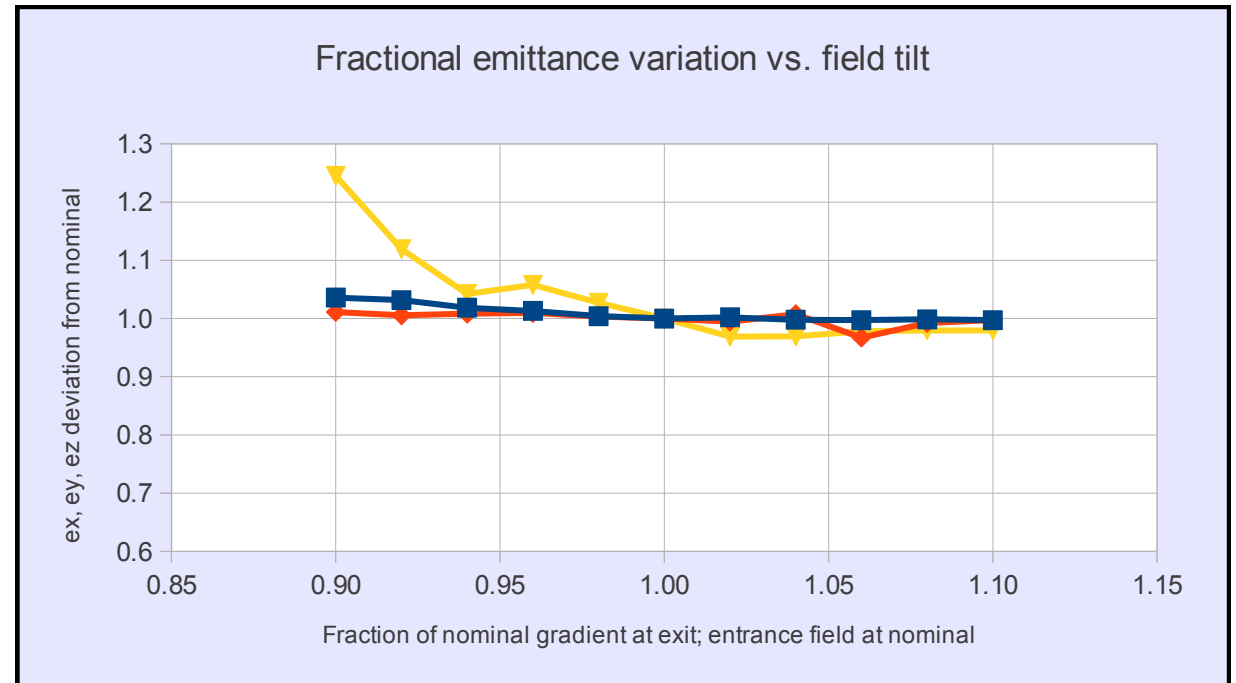
Effect on output emittance and deviation from nominal output energy as a function of **field tilt error**, pivoting around zero field error in the center of the RFQ.



Independent Parameter:

Field tilt at exit

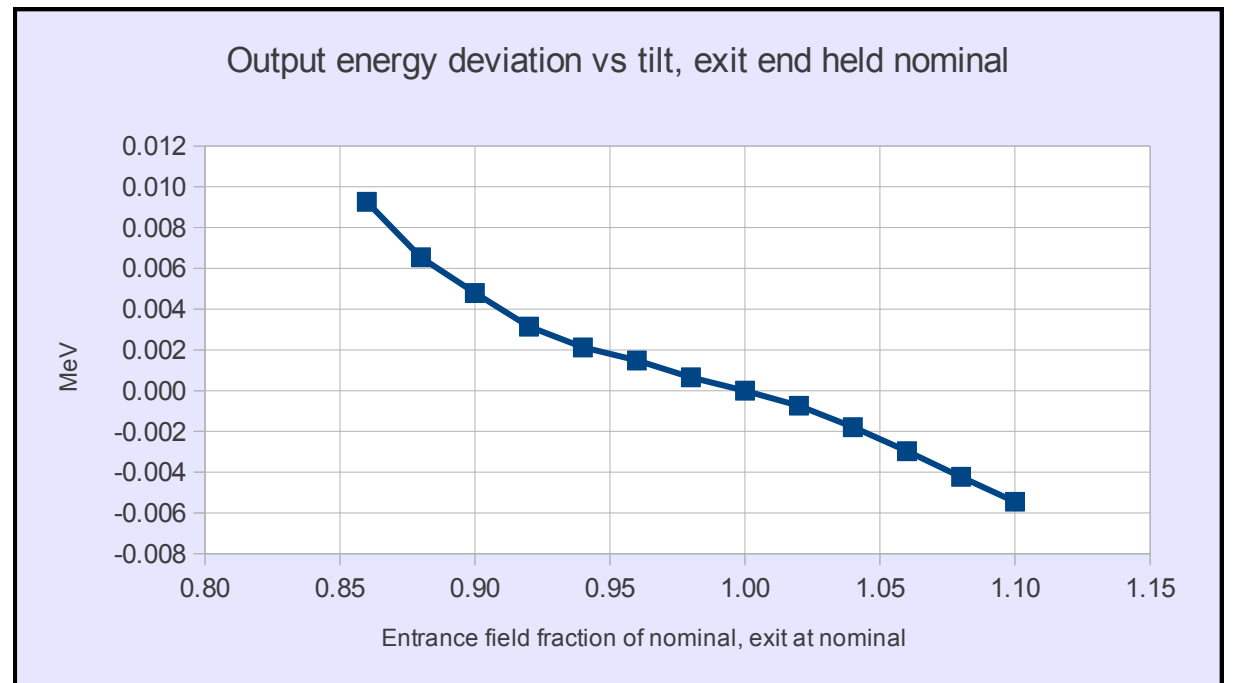
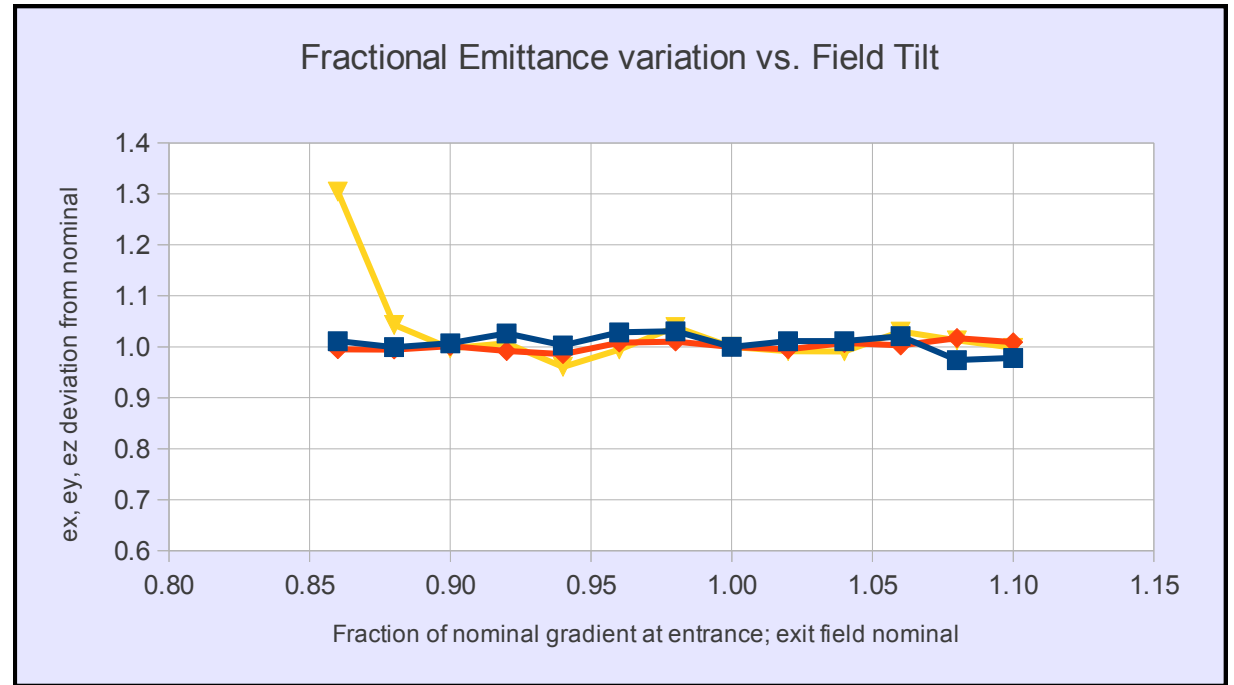
Output emittance and deviation from nominal energy for **zero** field error at **entrance**, **maximum** at RFQ exit.



Independent Parameter:

Field tilt at entrance

Output emittance and deviation from nominal energy for **zero** field error at **exit**, **maximum** at RFQ entrance.



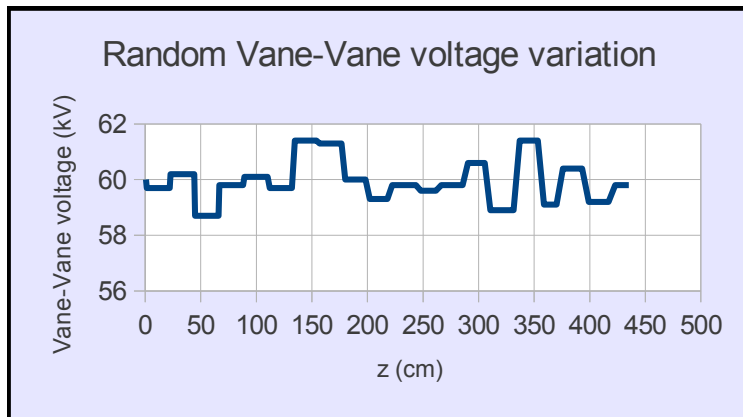
Independent Parameter:

Random Field Errors along Z

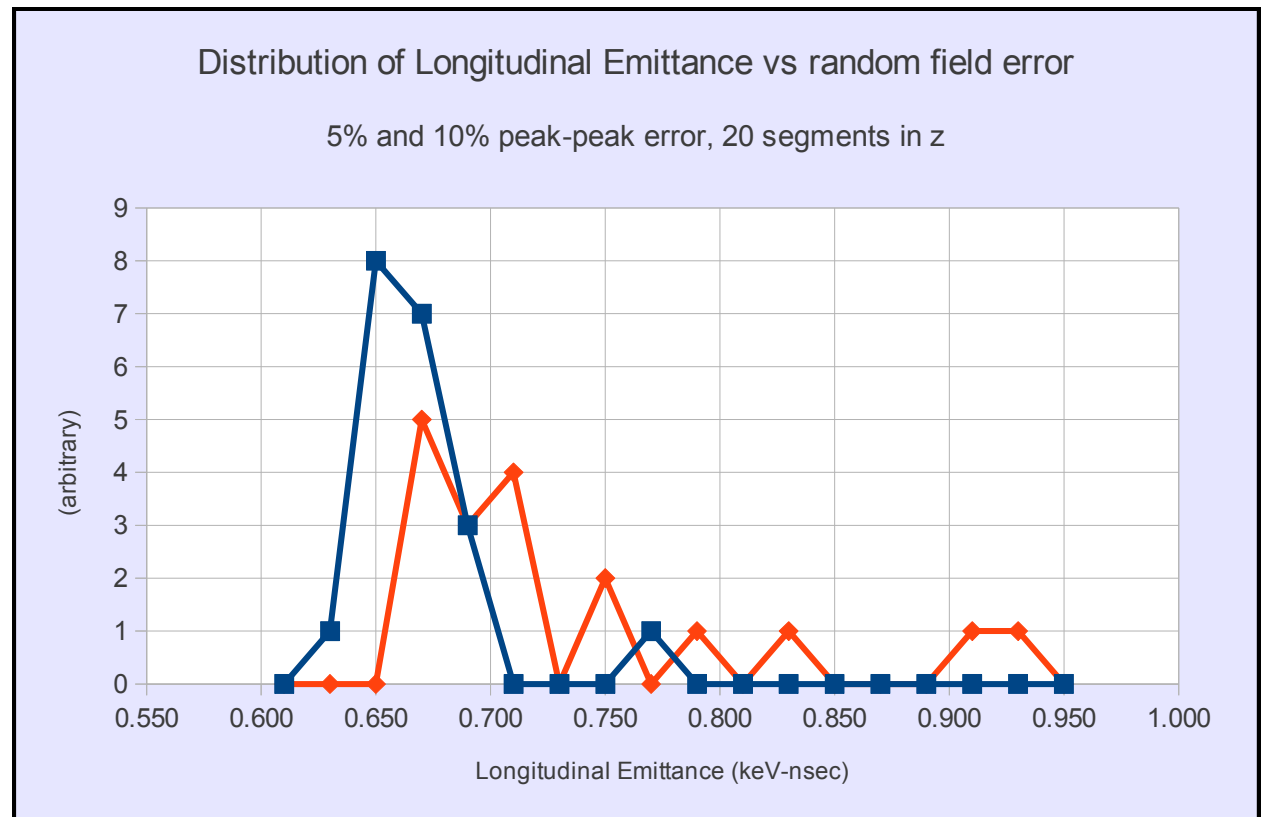
20 linacs each with 5% and 10% peak-to-peak random field error in each of 20 equal length segments along z, same distribution as number of tuners.

Almost no effect on transverse emittance or capture. Plot histogram of output longitudinal emittance in MeV-deg.

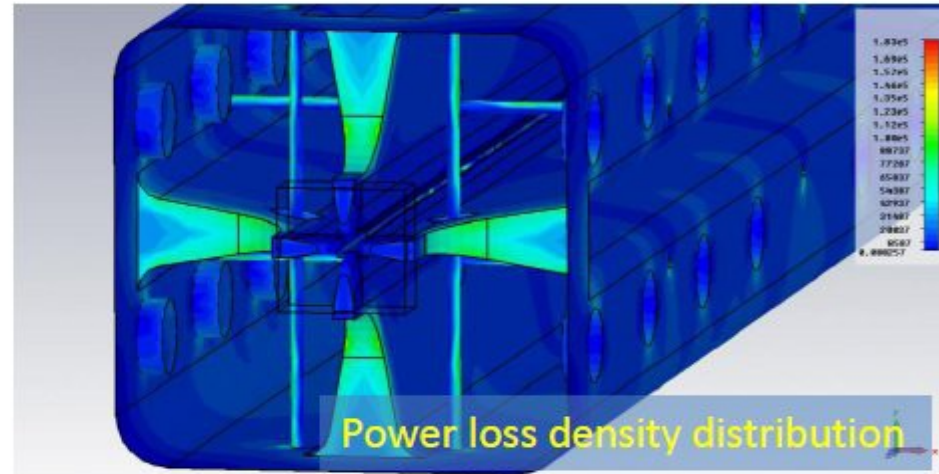
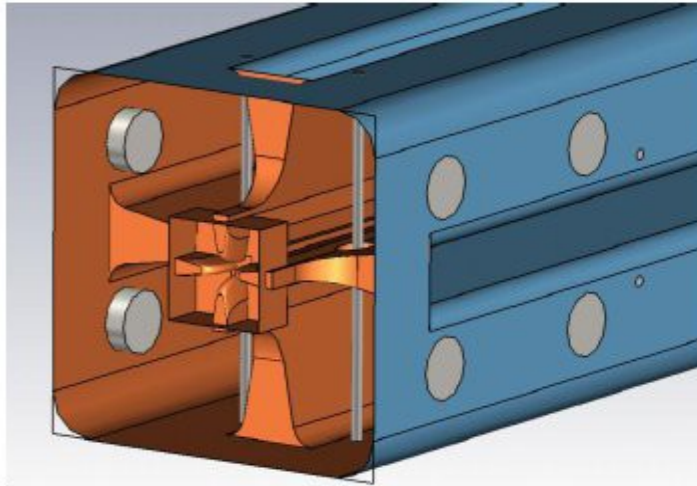
Zero error longitudinal emittance is 0.038 MeV-deg = 0.65 keV-nsec



Sample random voltage variation along RFQ.



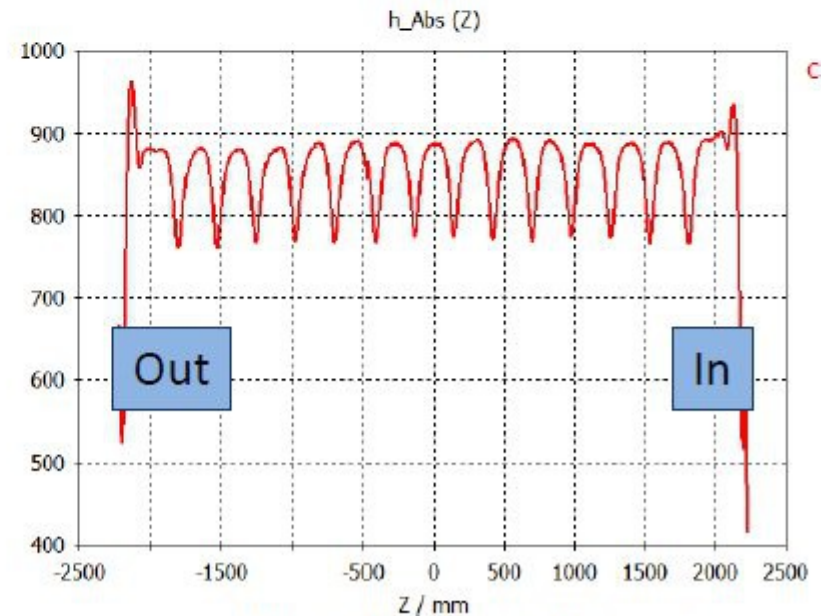
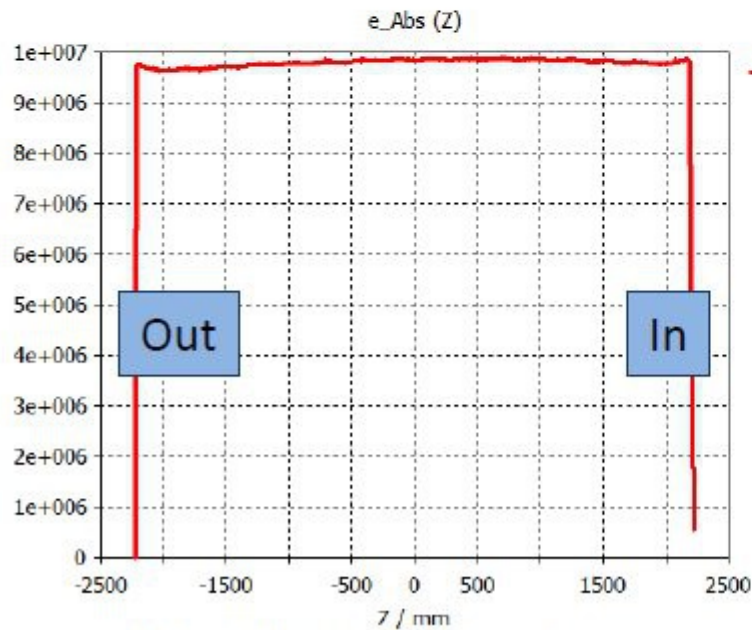
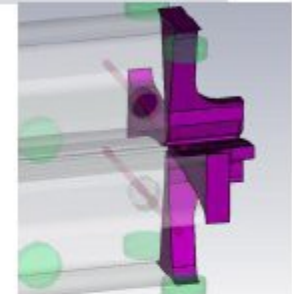
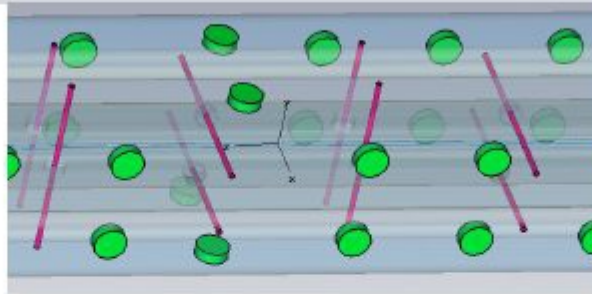
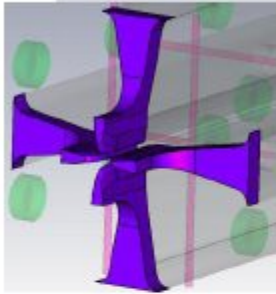
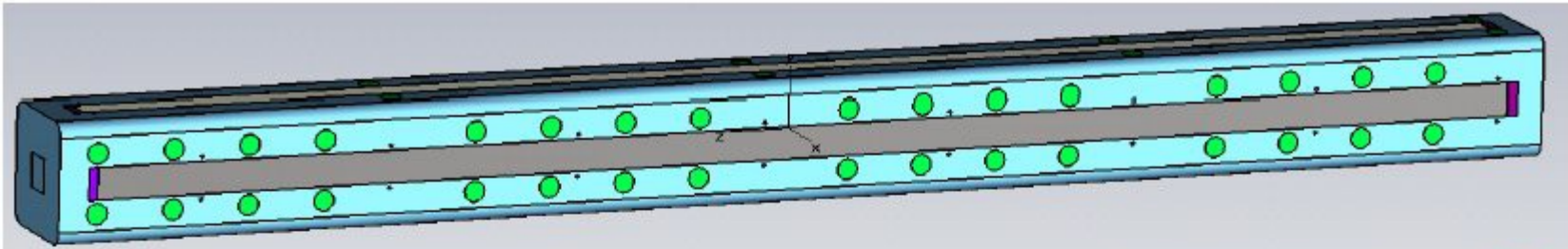
Pi-Mode Stabilizer Simulations (G. Romanov)



Parameters	IMP	PXIE-T	
Frequency, MHz		162.493	
Frequency of dipole mode, MHz		181.99	
Q factor		14660	
Q factor drop due to everything, %		-14.7	
Power loss per cut-back, W (In/Out)		336/389	
Max power loss density at cut-back, W/cm ²		7.9	To be verified
Total power loss, kW		73.8	
H, mm		172.73	

Quadrupole-Dipole frequency separation is **17.1 MHz**.

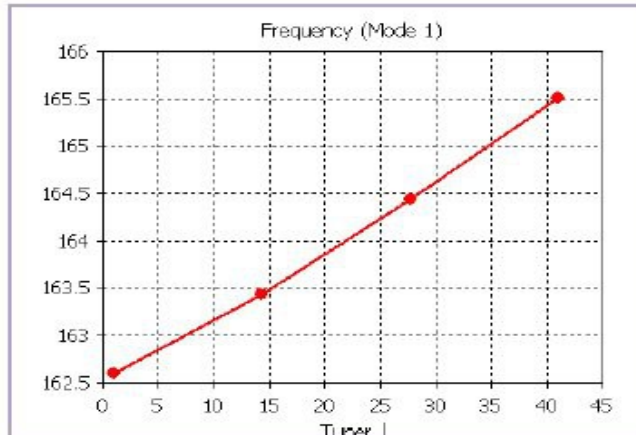
MWS Calculation of Effect of Tuners on Field Flatness (G. Romanov)



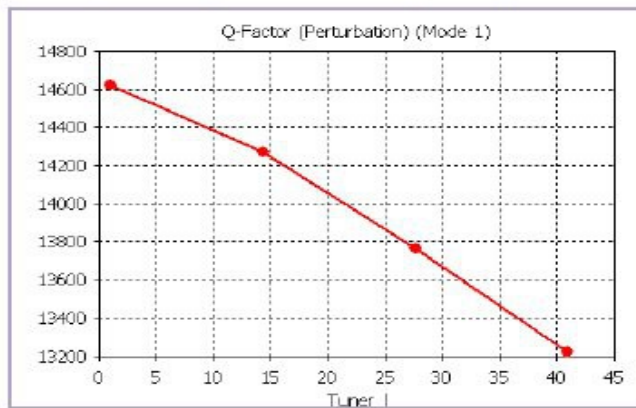
Field Ripple due to the Tuners (G. Romanov)

Effect of the plug tuners.

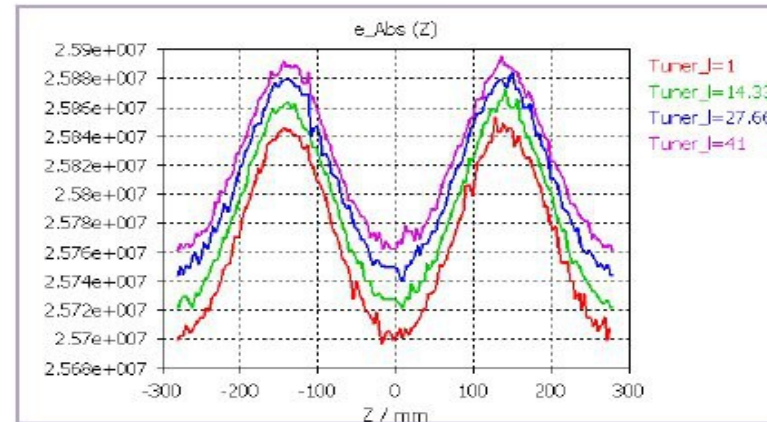
Tuner diameter – 60 mm,
Penetration 0-40 mm



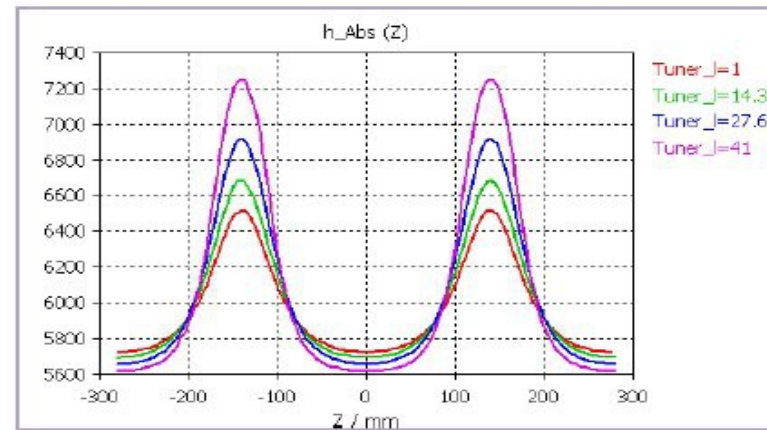
Operating mode frequency



Q-factor



E_{abs} in the gap ($X=Y=5$ mm) vs Z . No visible changes.



H_{abs} in the center of quadrant ($X=Y=100$ mm) vs Z .

Tuner sensitivity = 0.75 MHz/cm. Peak field ripple on axis less than 0.5% p-p.

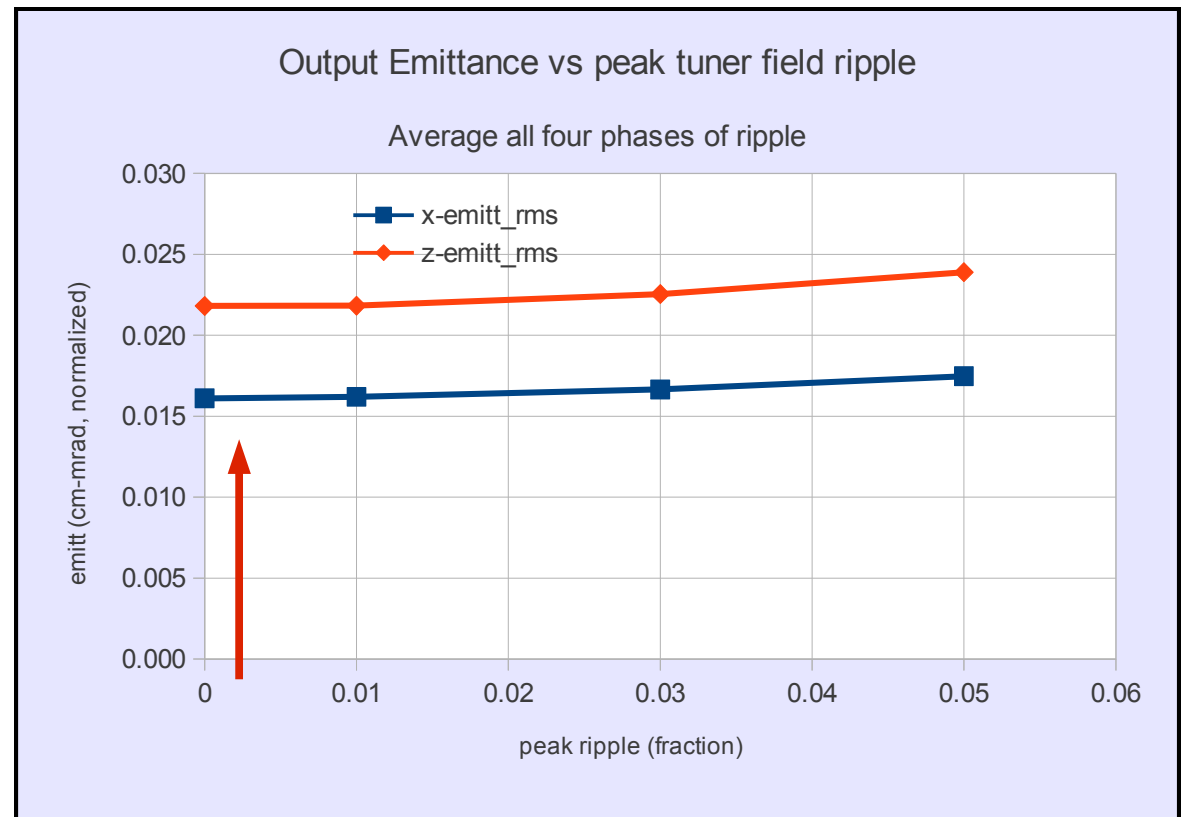
Output Emittance vs. Tuner Ripple on the Field Distribution

The 20 equi-spaced tuners in each quadrant produce a variation in the field distribution. The peak-to-peak variation of the accelerating field is less than 1%, but is larger in the outer region near the tuners.

An alternate version of Parmteq was modified to include the tuner ripple on the beam axis. The output emittance for four phases (+sin, +cos, -sin, -cos) of the ripple were averaged, as the absolute phase, relative to the position along the axis, will not be known until the RFQ is tuned.

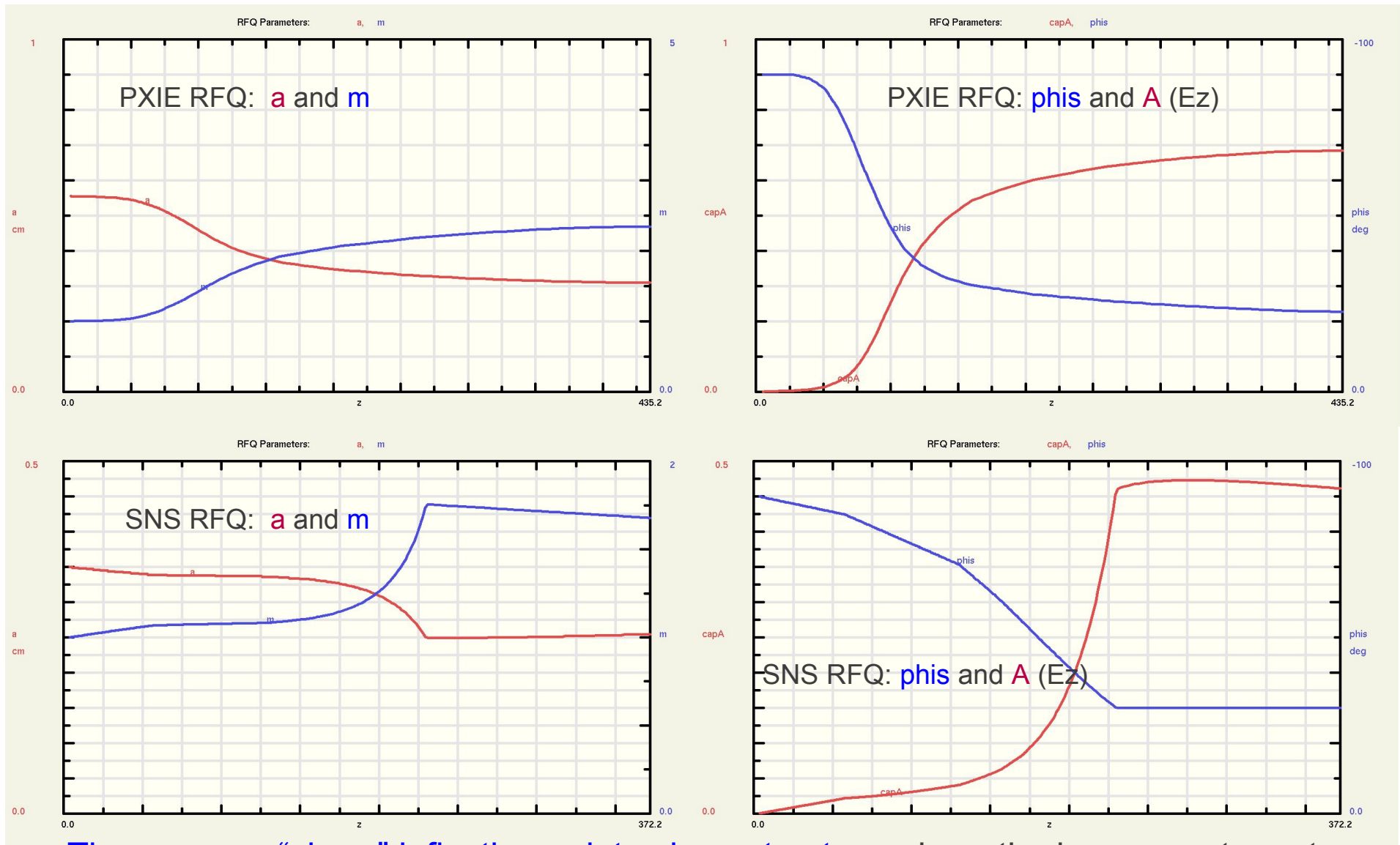
MWS simulation shows a p-p ripple of 0.5% at 5 mm from the axis, corresponding to a peak fraction of 0.0025 on the plot (near zero).

The ripple in the field due to the tuners will **not** result in a measurable emittance increase.



Why is this design so error tolerant?

Compare parameters to SNS RFQ, which is designed for much higher current.



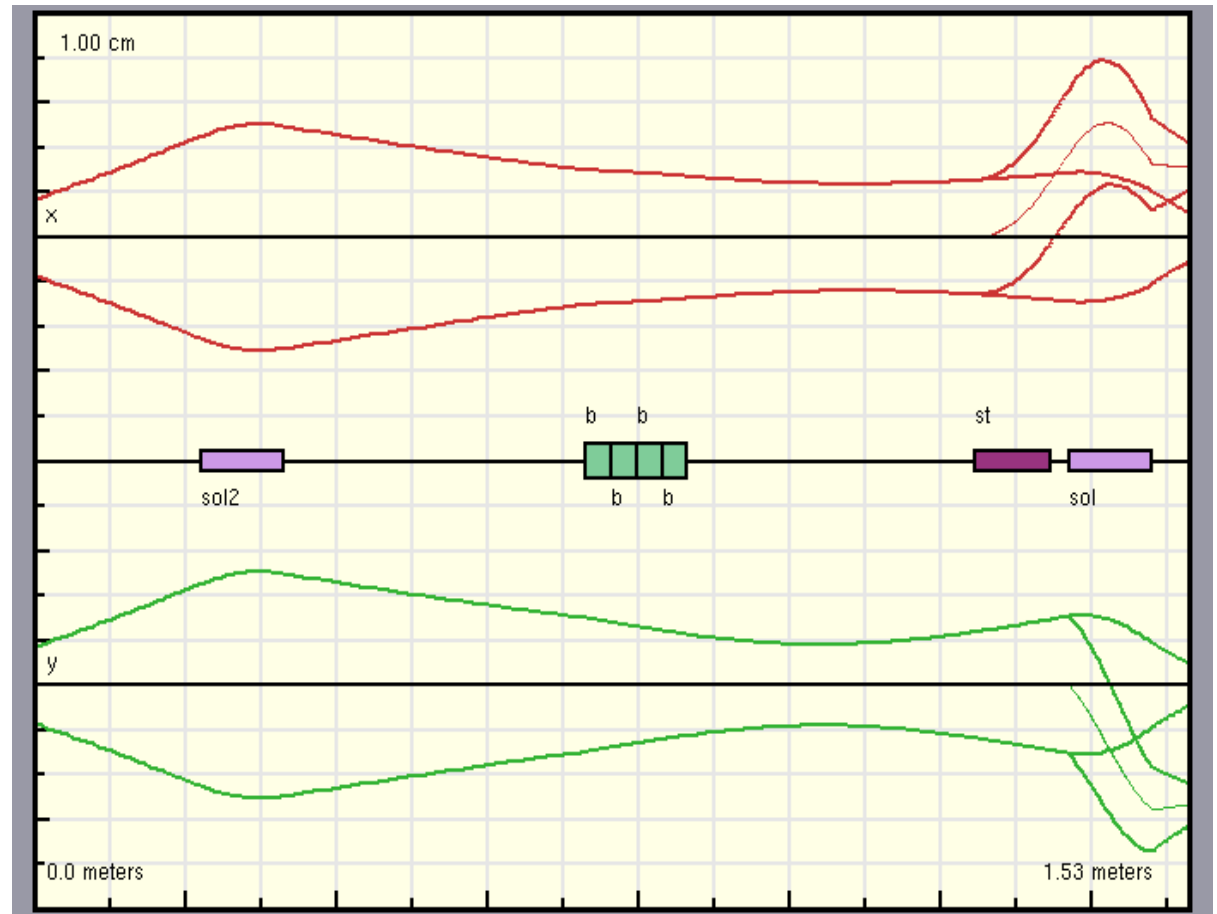
There are no “sharp” inflection points along structure where the beam must meet criteria of proper bunch shape, space charge density, etc. The PXIE aperture is large. Most of the length of the PXIE RFQ is devoted to acceleration (plotted vs. z). Also, the PXIE RFQ has a larger aperture, thus larger transverse acceptance.

RFQ Transmission with LEBT Chopper

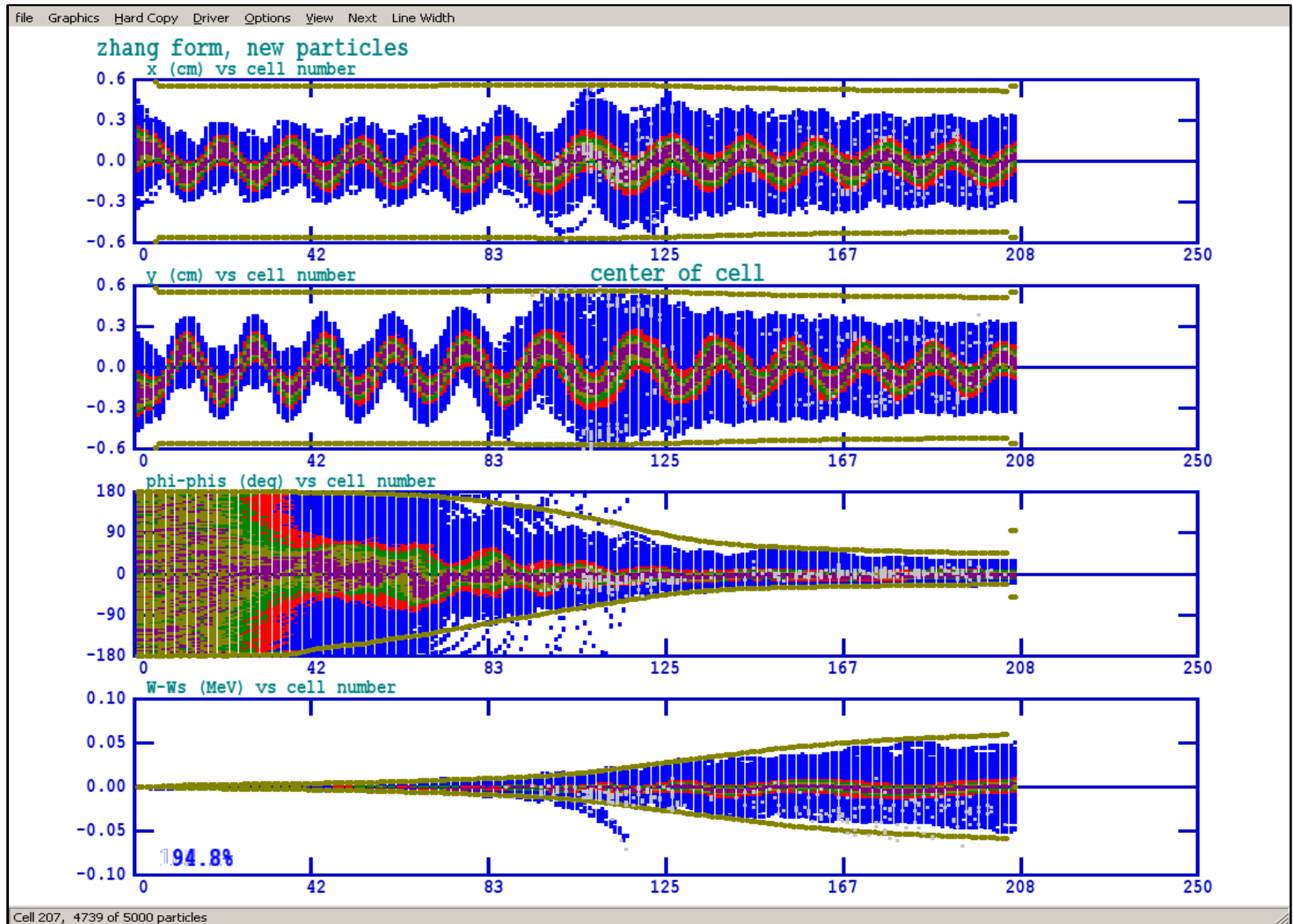
The 2-solenoid LEBT chopper places a parallel-plate deflector in front of the final focusing solenoid. A 0.5 cm radius aperture is placed in the entrance flange of the RFQ.

The maximum chopping frequency is 1 MHz to reduce the average beam current to 1 mA.

The rise/falltime of the beam due to the risetime of the electronics and the transit time of the beam through the 10-long chopper is less than 50 nsec. During this time, the beam will still be captured by the RFQ and sent to the MEBT.



Beam Trajectory of partially chopped beam. About 12 betatron oscillations.



What goes in of axis comes out off axis.

RFQ Entrance Aperture

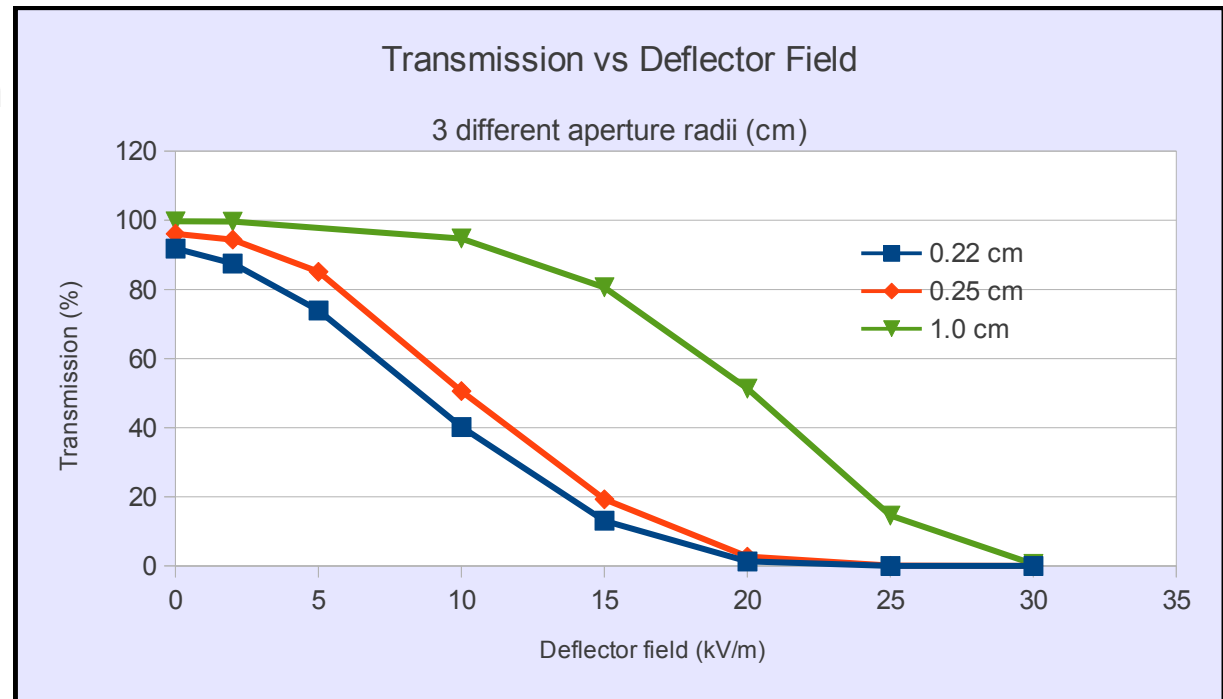
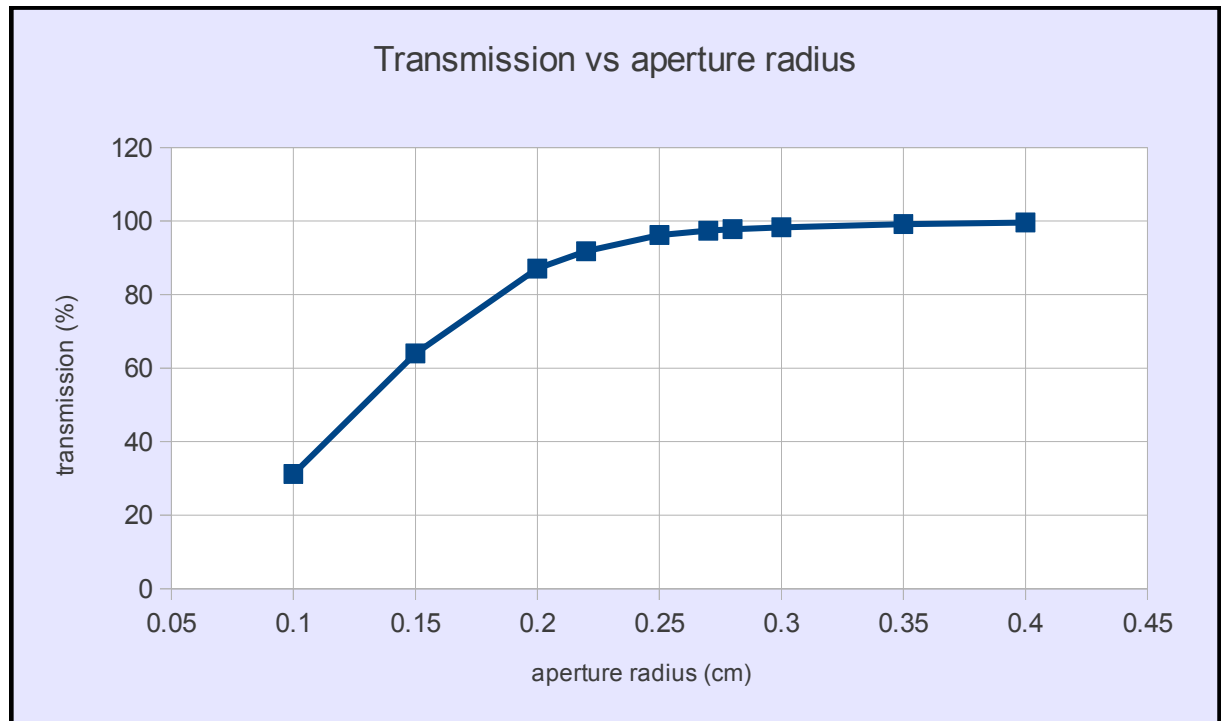
Transmission through the RFQ of **unchopped beam** as a function of an aperture at the entrance with given aperture radius

The beam distribution is derived from the emittance measurement and includes halo particles.

The LEBT chopper field requires at least 30 kV/m (± 465 volts across a 3.1 cm gap) to extinguish the beam. A larger field will be available.

Transmission through the RFQ of the **chopped beam** for three different aperture radii as a function of the field on the 11 cm long chopper.

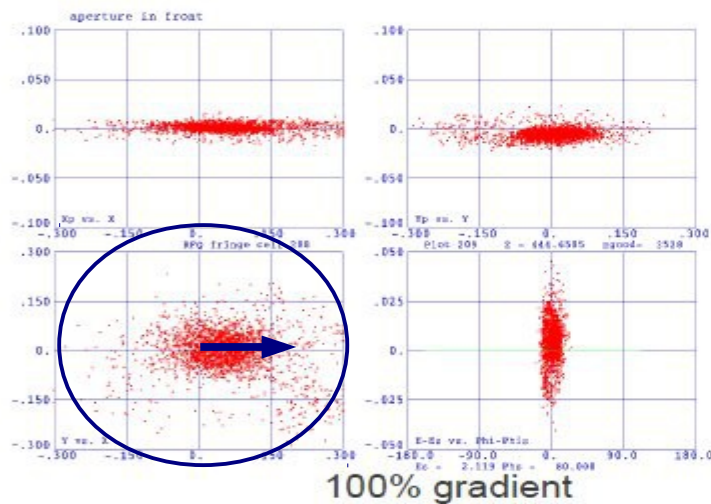
The baseline entrance aperture radius is **0.25 cm**.



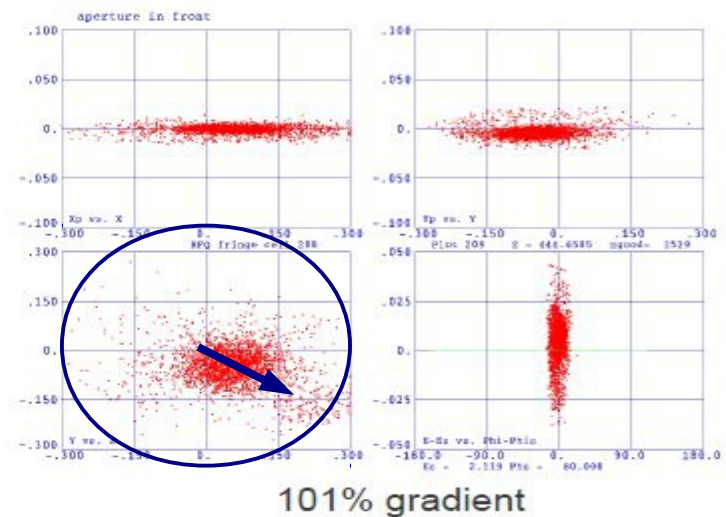
Worst-case (half-chop) particle distributions as a function of detailed RFQ gradient. There are about 12 transverse betatron oscillations along the RFQ structure. A 2% gradient increase adds about another quarter oscillation. The orbit of the partially chopped beam from the RFQ depends strongly on the actual operating gradient.

10 kV/m chop, 51% transmission, vary RFQ gradient

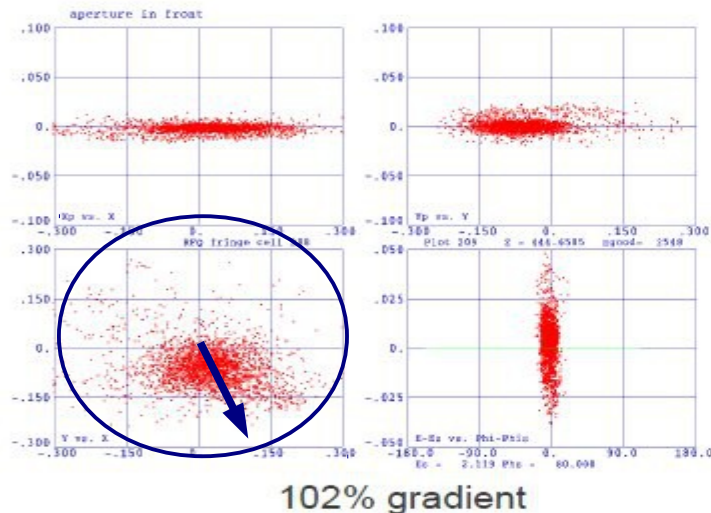
Output beam details depend on number of betatron oscillations.



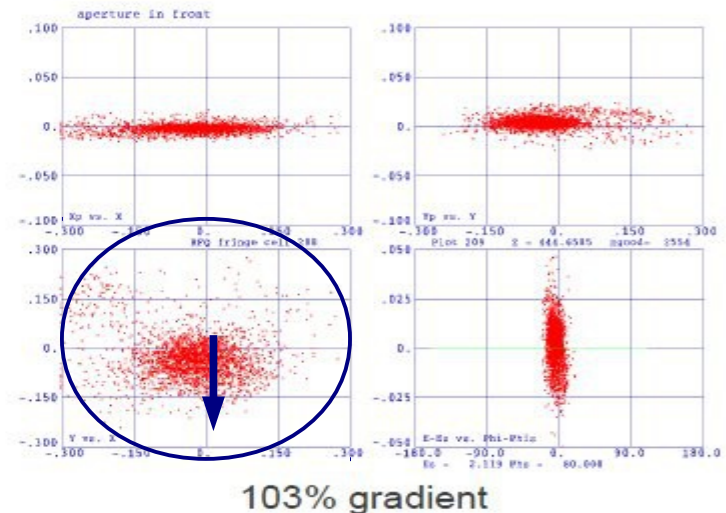
100% gradient



101% gradient



102% gradient

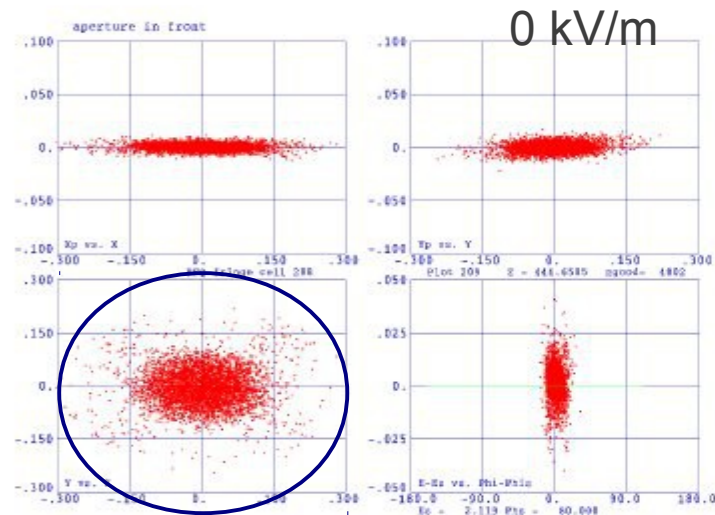


103% gradient

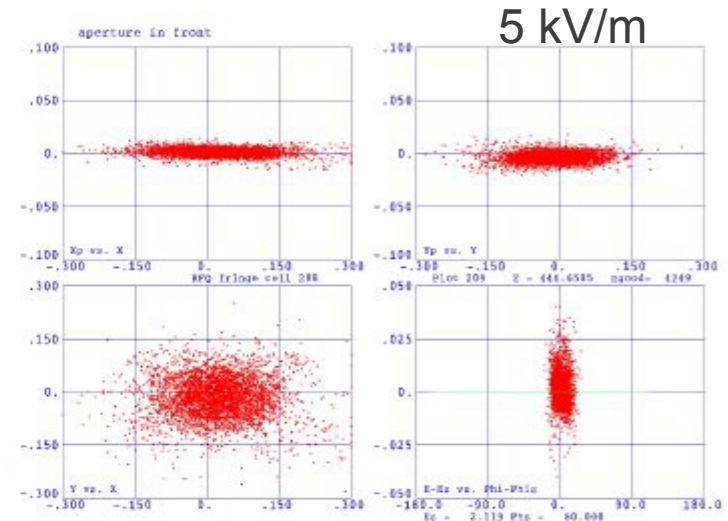
Particle and phase space distributions at the RFQ exit for various chopper fields.

Almost all of the partially chopped beam stays within the unchopped beam profile

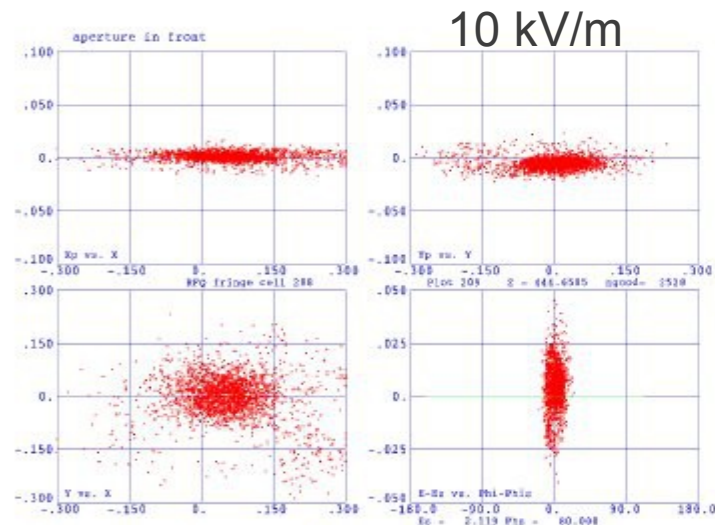
Output Phase Space vs. LEPT Chopper Field, 0.25 cm radius entrance aperture



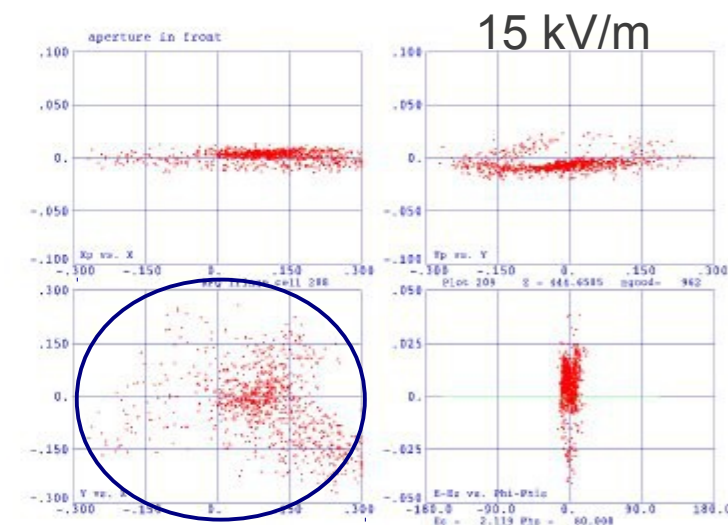
0 kV/m chop, 96.1% transmission



5 kV/m chop, 85.1% transmission

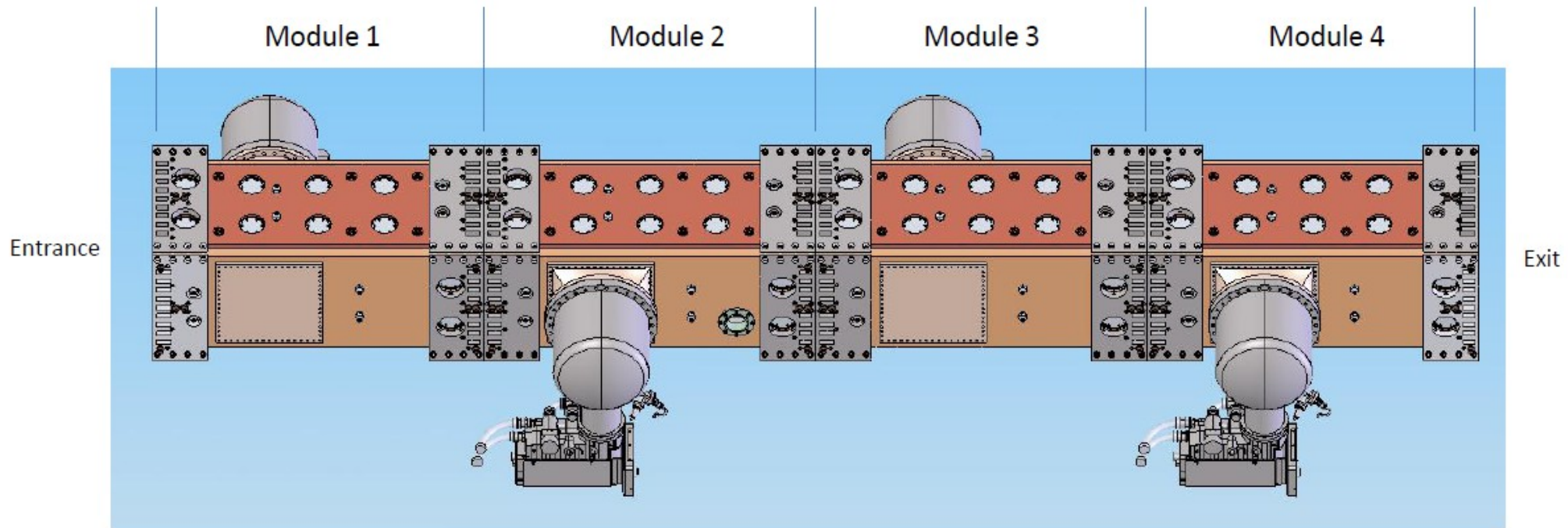


10 kV/m chop, 50.6% transmission



15 kV/m chop, 19.3% transmission

RF Structure

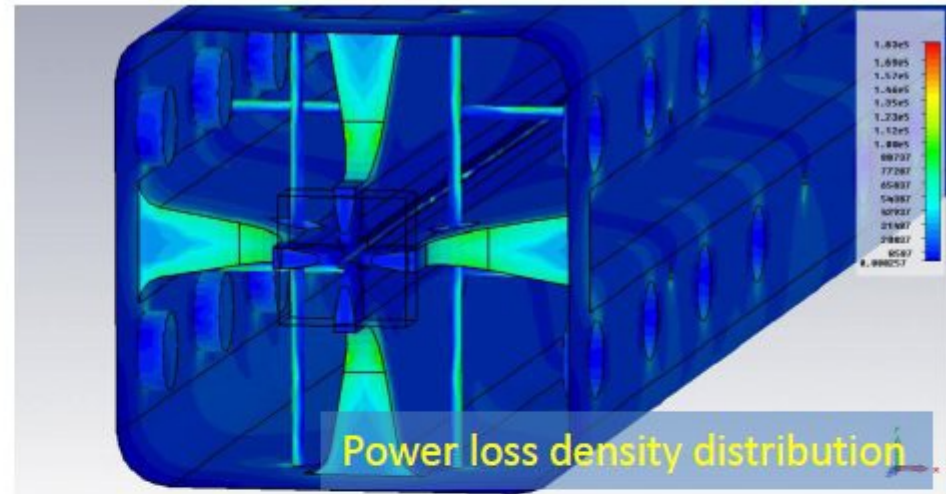
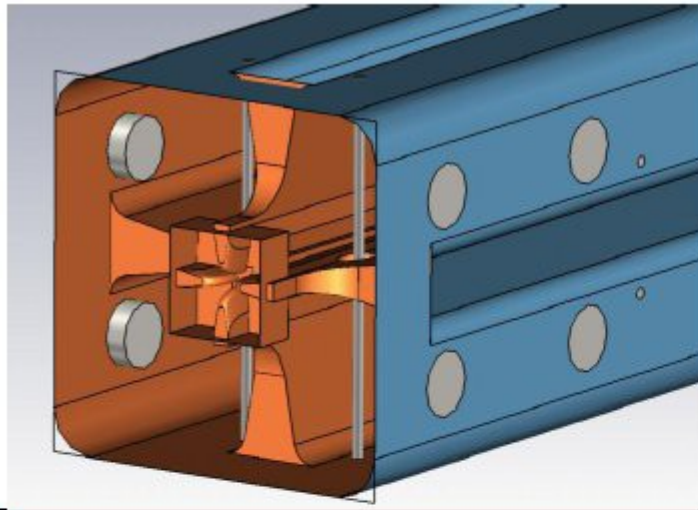


Structure is 444.6 cm long in four modules.

32 pi-mode stabilizers, 4 pairs in each module separate the dipole frequency to 17 MHz above the 162.5 MHz quadrupole frequency

80 tuners, 20 in each quadrant have a diameter of 6 cm, a nominal insertion of 2 cm, and a tuner sensitivity of 170 kHz/cm, all tuners moving together.

MWS Calculation of Cavity Frequency, Power Loss (G. Romanov)



Parameters	IMP	PXIE-T	
Frequency, MHz		162.493	
Frequency of dipole mode, MHz		181.99	
Q factor		14660	
Q factor drop due to everything, %		-14.7	
Power loss per cut-back, W (In/Out)		336/389	
Max power loss density at cut-back, W/cm ²		7.9	To be verified
Total power loss, kW		73.8	
H, mm		172.73	

Distribution of Power Loss on RFQ Components (G. Romanov)

Part	Total, kW	Per unit, W	Percent
Walls	29.5	-	40
Vanes, 4 units	31	7764	42
Input cut-backs, 4 units	1.34	336	1.8
Output cut-backs, 4 units	1.56	389	2.1
Pi-mode rods, 32 units	5.53	173	7.5
Tuners, 80 units	4.79	59.9	6.5

Total power loss for **ideal copper**, no joint loss is **73.7 kW**. With a **30% margin** for anomalous losses, the **cavity power requirement is 96 kW**. Additional losses will occur in the drive loops, coaxial waveguide and circulators.

Multipactoring in the RFQ Cavity

Multipactoring can occur in the cavity and in the RF drive lines.

Cavity multipactoring was investigated with FISHPACT, on a 2-D slice of cavity.

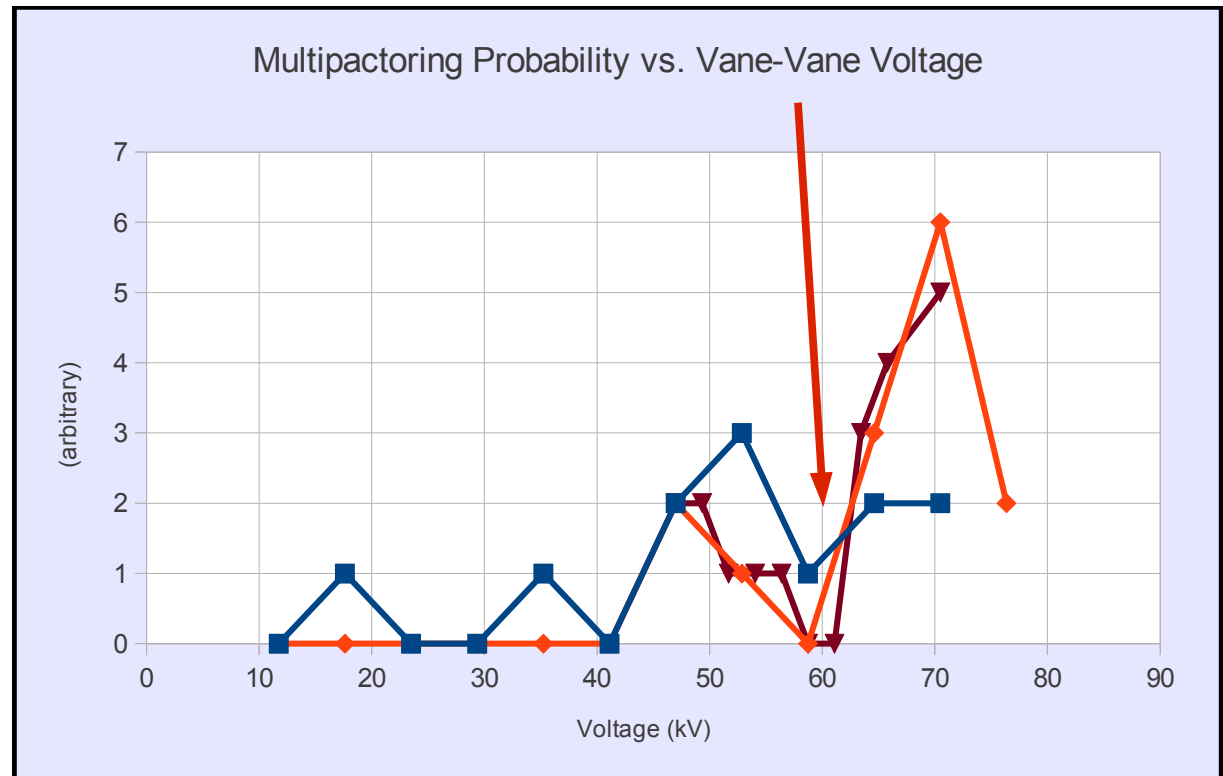
Fishpact was used for the APEX photoinjector cavity, which shows no MP activity.

Fields were stepped over the range of operation, with emitting spots at locations around the periphery, and 6 RF start phases from 0 in steps of 60 degrees.

Three FISHPACT runs with different search parameters show a minimum of activity at 60 kV vane-vane voltage.

All activity is on the outer boundary of the cavity, where the electric field is low and is less likely to pull an electron off the surface.

No activity is noted near the vanetips in the high E-field zone. The electron energy is high so the SEY < 1.0.



It is expected that no significant multipactoring will occur in the cavity.

RF Driveline Multipactoring

The **APEX photoinjector** runs 100 kW CW at 187 MHz (1.3 GHz / 7) and has two loop couplers, each delivering 50 kW.

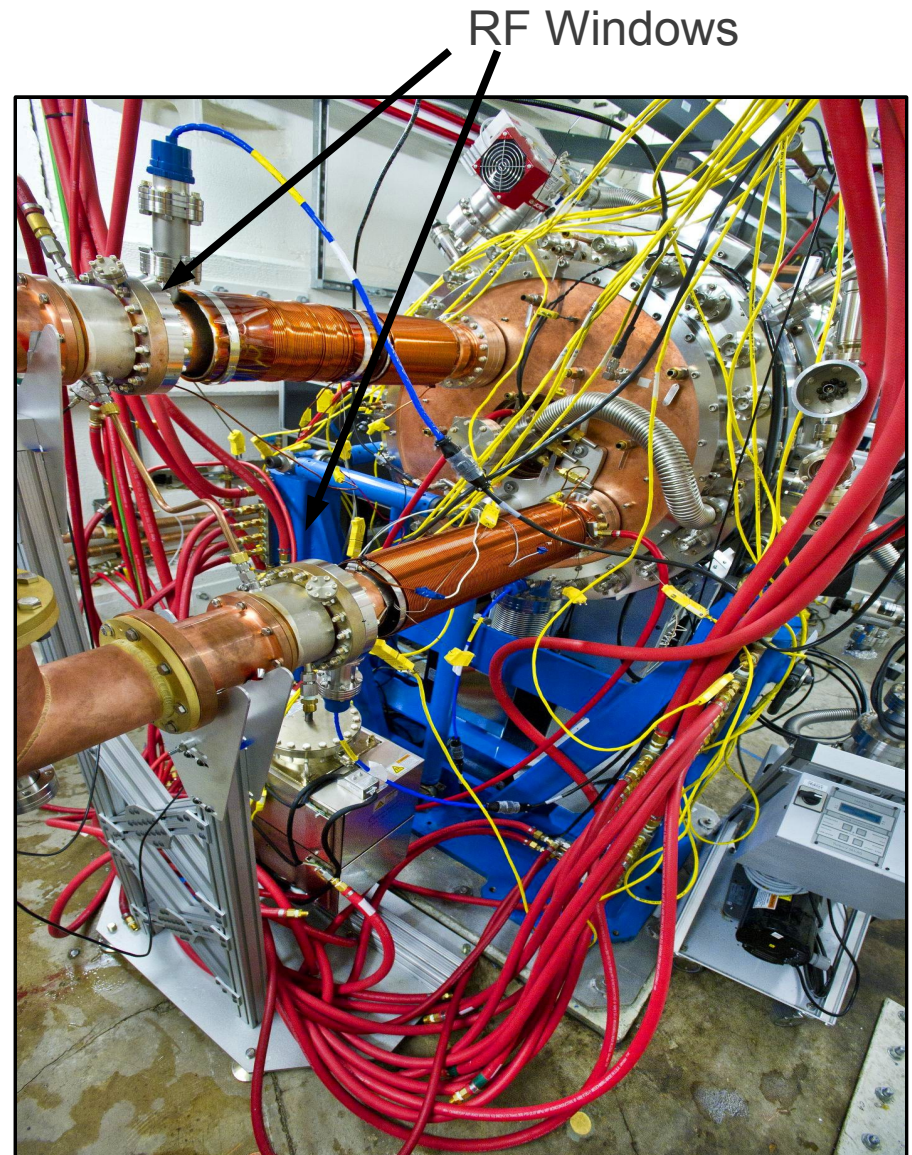
The RF windows are located 90 cm away from the drive loops.

Severe multipactoring in the vacuum sections of the drive lines was observed.

The multipactoring was suppressed by surrounding them with **100 gauss solenoid coils**.

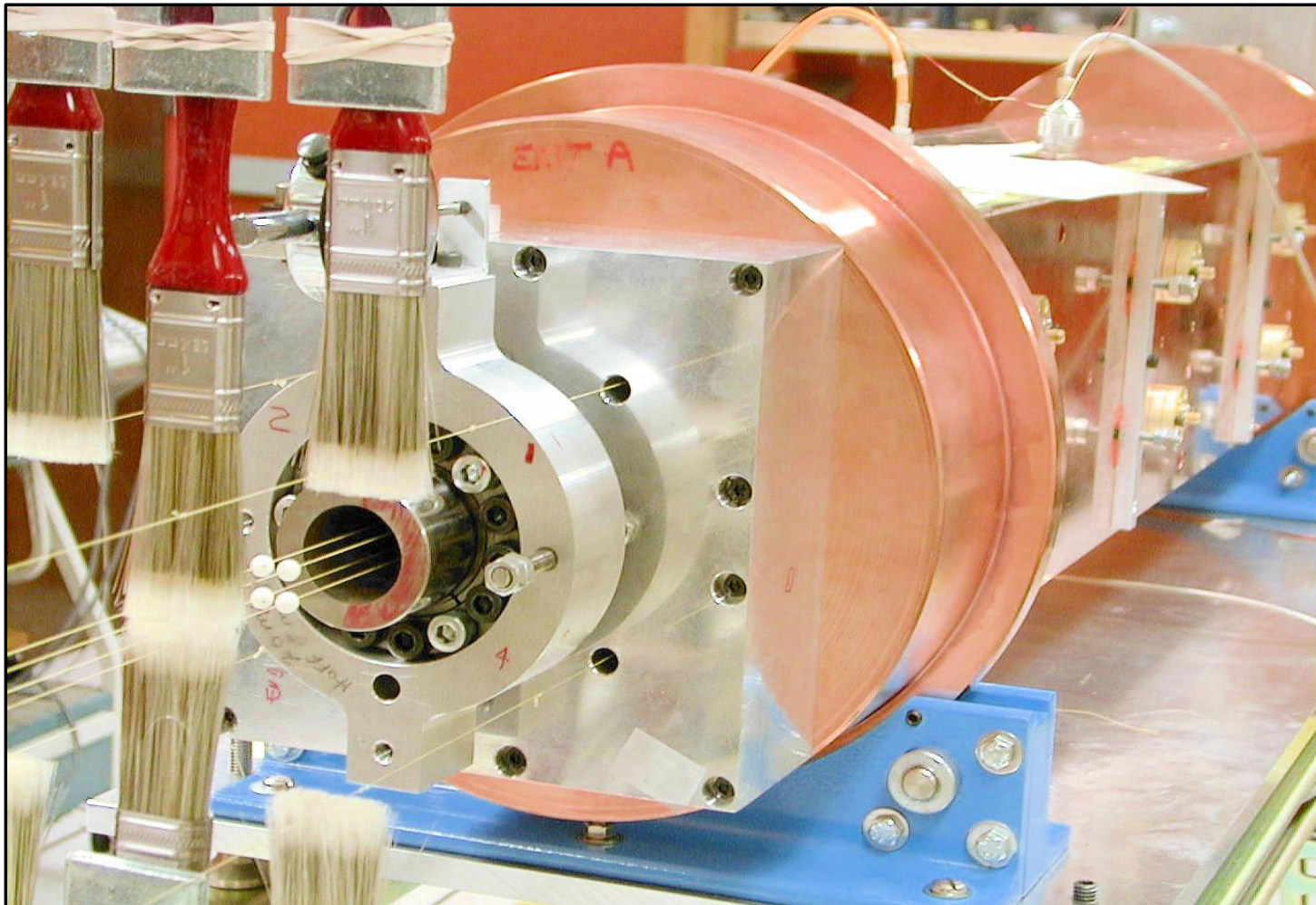
We may shorten the drive lines and move the windows much closer to the coupling loops to eliminate possible magnetic fields at the photocathode.

A similar situation may affect the PXIE RFQ drive lines and should be taken into account.



Tuning the RFQ

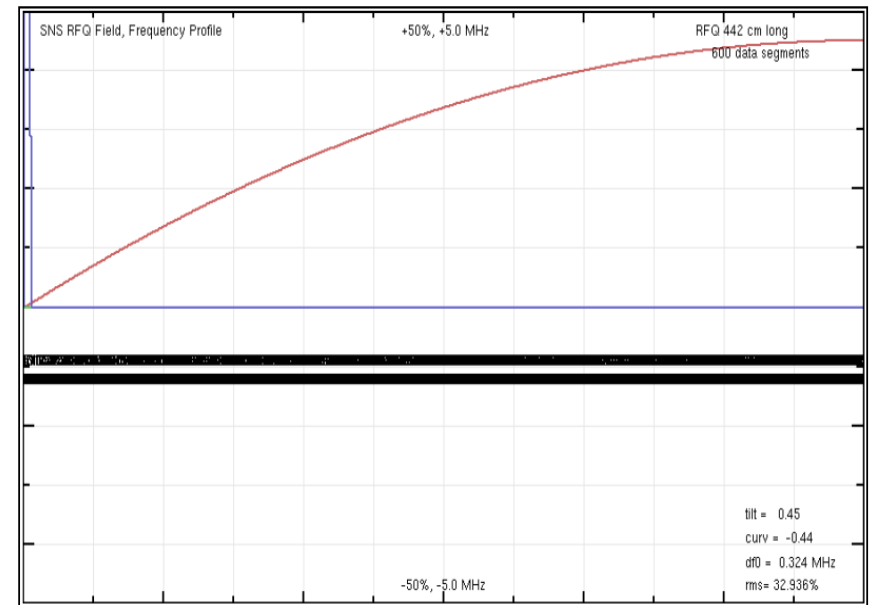
The RFQ will be tuned with a bead-pull of a substructure and of the entire structure, and the 48 sensing probes, 3 / quadrant / module will be calibrated. We will pull only one bead in one quadrant as **the pi-mode stabilizers strongly lock the fields in the four quadrants together**. (Picture is of SNS 1-module cold model.)



Perturbations to Field Flatness: Tuning

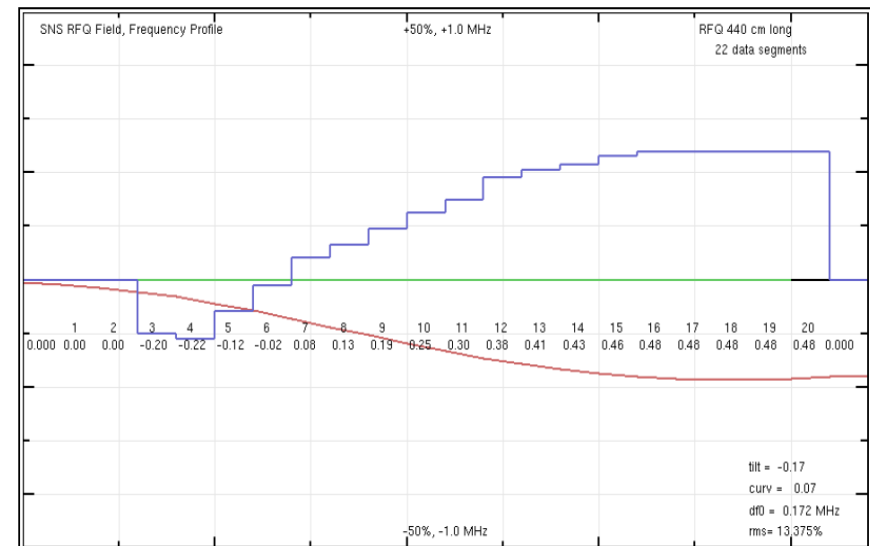
Entrance 6-cell radial matcher

Frequency perturbation of +0.33 MHz causes an uncorrected **field tilt of +45% at the exit**.
Corrected by modifying the entrance end cutbacks in the vanes



Effect of the modulations of the vane tips

Local frequency variation -0.2 to +0.5 MHz, or an overall perturbation of +0.17 MHz, causing a **field tilt of -18% at the exit**.
Corrected by the local tuners.



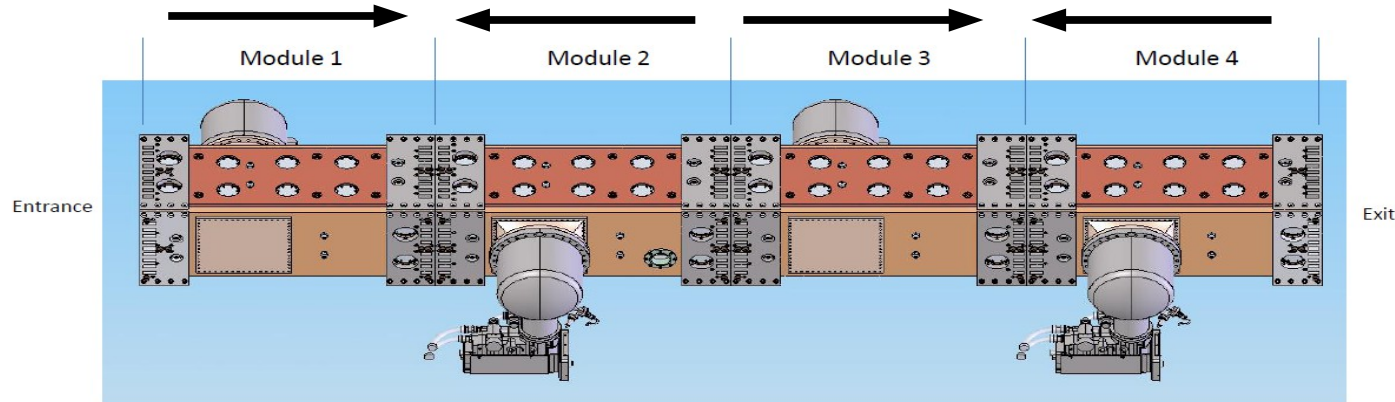
Group tuner sensitivity: +0.46 MHz/cm.
Initial tuner insertion is 2 cm, or +0.92 MHz.

Pi-Mode Stabilizers: -4.5 MHz frequency shift

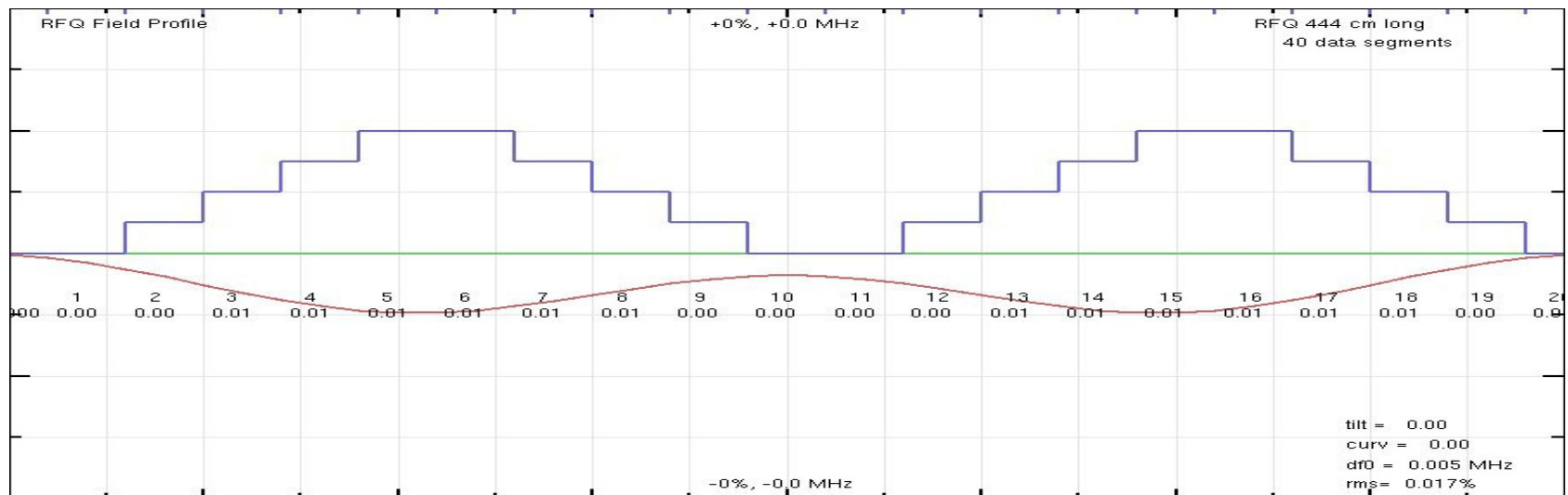
“Bare” (Superfish) frequency about 3 MHz high before tuners, stabilizers and ends added.

Field Perturbation from Cold to Hot

The waterflow circuits in each of the four modules will be in the following directions:



The change in water temperature in each module produces a frequency shift of 10 kHz from one end to the other (blue). This results in a variation of the field of 0.025% peak-peak (red).



This field variation will not be present during low-level tuning and will not be significant for full-power operation.

Lessons Learned from other RFQs

Most run just fine, but there have been problems with some.

SNS: Two instances of frequency jumps with field redistribution. Required retuning. Pi-mode stabilizers probably kept the fields close to nominal even though a quadrant asymmetry may still exist. Investigated thoroughly, cause not found. RFQ continues to operate satisfactorily.

Other RFQs:

- Sloppy assembly

- Inability to gain access to structure through surrounding jacket

- Insufficient thermal capability at required gradients

- Poor mechanical design

- Four-rod warping problem

- Poisoning from severe vacuum accident

- Discharges due to poor vacuum at entrance

PXIE RFQ: None of the above problems are expected for the PXIE RFQ.

The thermal wall loading is 1/3 of SNS, the peak gradient is 1.2 kilpatrick.

Possible multipactoring problems with the drive loops has been recognized.

The water passages are gun-bored into the structure itself: no exoskeleton.

Vacuum at the RFQ entrance will be in the low 7's due to a small entrance aperture and a 1.5 meter distance from the ion source. Beam loss in the RFQ, including chopping, is expected to be very small.

Recap: Issues Addressed

Design frozen: final engineering proceeds

Easily meets requirements

High acceptance, 0-10 mA characteristics, low output divergence

Error Analysis

Current dependence

Beam quality dependence on field errors

Large field errors results in small emittance growth

RF Design

Stabilizers, mode separation, tuning

Large separation of quadrupole and dipole modes

Large immunity to asymmetry and machining errors

RF Power issues

Power distribution within structure

No expected multipactoring in cavity, but watch drive lines.

Lessons learned from other RFQs

Design avoids issues that have arisen in other RFQs